Sustainability of biogas production from biomass waste streams: Grass & cow manure co-digestion process

By

Christian van Someren

Postgraduate Program Renewable Energy

Carl von Ossietzky University, Oldenburg, Germany

Hanze University of Applied Science, Groningen, Netherlands

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Supervisors:

Dr. Ing. Alexandra Pehlken, Carl von Ossietzky University, Oldenburg, Germany

Frank Pierie, PhD researcher, Hanze University of Applied Science, Groningen, Netherlands

Examination Date: March 17, 2014

Examiner 1: Prof. Dr. Jürgen Parisi, Carl von Ossietzky University, Oldenburg, Germany

Examiner 2: Dr. Ing. Alexandra Pehlken, Carl von Ossietzky University, Oldenburg, Germany

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Abstract

Biogas plays an important role in many future renewable energy scenarios as a source of storable and easily extracted form of renewable energy. However, there remains uncertainty as to which sources of biomass can provide a net energy gain while being harvested in a sustainable, ecologically friendly manner. This study will focus on the utilization of common, naturally occurring grass species which are cut during landscape management and typically treated as a waste stream. This waste grass can be valorized through co-digestion with cow manure in a biogas production process. Through the construction of a biogas production model based on the methodology proposed by (Pierie, Moll, van Gemert, & Benders, 2012), a life cycle analysis (LCA) has been performed which determines the impacts and viability of using common grass in a digester to produce biogas. This model performs a material and energy flow analysis (MEFA) on the biogas production process and tracks several system indicators (or impact factors), including the process energy return on energy investment ((P)EROI), the ecological impact (measured in Eco Points), and the global warming potential (GWP, measured in terms of kg of CO_2 equivalent). A case study was performed for the village of Hoogkerk in the north-east Netherlands, to determine the viability of producing a portion of the village's energy requirements by biogas production using biomass waste streams (i.e. common grass and cow manure in a co-digestion process). This study concludes that biogas production from common grass can be an effective and sustainable source of energy, while reducing greenhouse gas emissions and negative environmental impacts when compared to alternate methods of energy production, such as biogas produced from maize and natural gas production.

"The ultimate goal of farming is not the growing of crops, but the cultivation and perfection of human beings."
― Masanobu Fukuoka, *The One-Straw Revolution*

This research paper is dedicated to all the great friends I made over the past two years. I couldn't have done it without you guys!

Declaration

I state and declare that this thesis was prepared by me in accordance with the best practice guidelines for scientific work of the University of Oldenburg and that no means or sources have been used, except those, which I cited and listed in the References section the research project: **Sustainability of biogas production from biomass waste streams: Grass & cow manure co-digestion process.**

Christian van Someren　　　　　　　　　　Date

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Abbreviations Used	
CHP	Combined Heat and Power
DM	Dry Matter content
Eco Points	Ecological Impact Points
(P)EROI	(Process) Energy Return On Energy Invested
FM	Fresh (i.e. wet) Mass
GWP	Global Warming Potential
Kg CO_2 eq	Kilograms of Carbon Dioxide Equivalent
LCA	Life Cycle Analysis
LM	Landscape Management
LST	Life Science and Technology Department of Hanze University of Applied Science
MEFA	Materials and Energy Flow Analysis
Nm^3	Normal cubic meter
ODM	Organic Dry Matter
TNO	Netherlands Organisation for Applied Scientific Research
Vol%	Volume Percent
VS	Volatile Solids
VSS	Volatile Suspended Solids
Wt%	Weight Percent

1 Introduction

With the increased focus on developing renewable energy technologies come several associated dilemmas. One identified issue with the transition towards renewable energy is the need to develop a source of balancing power to compensate for fluctuating solar and wind availability. Biomass is a source of renewable energy which employs organic materials (either in the form of energy crops or waste streams) to produce biogas (Twidell & Weir, 2006). Biogas is easily distributed, stored and accessed and can play an important role in future energy scenarios as a flexible and easily dispatched form of energy (Herzog, Lipman, & Kammen, 2001). However, the question arises as to whether or not biogas is truly a sustainable and renewable form of energy. If biogas production is not properly managed, more energy can be invested into the production process than is finally obtained (Belgrund & Borjesson, 2006). This is referred to as the process energy return on invested ((P)EROI) and describes the ratio of energy produced by a process to the energy required to operate this process. Additionally, the environmental impact (the relative effect of resource utilization and emissions on the environment, measured in Eco Points) and global warming potential (GWP, the relative contribution of a process towards global warming, measured in equivalent kilograms of carbon dioxide released to the atmosphere, or $kgCO_2eq$) of biogas production must be determined. These indicators must be determined in order to resolve the environmental sustainability of using biomass to produce energy. It is therefore important to study the life cycle of any biogas production process, to resolve the above-mentioned indicators while ensuring that this process can be operated in a sustainable way and provide a benefit to society.

Currently, cow manure mixed with energy crops, such as maize, is largely being used as a feedstock for anaerobic digesters (Vagonyte & Association, 2010). This study proposes that common grass may be a suitable alternative to traditional energy crops. Common grass can be defined as unsown, wild plant varieties which grow naturally on non-arable land, such as fallow fields, natural meadows, roadsides and ditches. Grassland is abundant throughout the world, covering 26% of total land area (Prochnow., et al., 2009), and grass has several distinct advantages as an exploitable source of biomass: Common grass has a large biodiversity and does not suffer from problems associated with monocultures altering ecosystems (Philip Robertson & Swinton, 2005); Common grass is naturally occurring and shows a lower negative ecological impact than annual crops (Uellendahl, et al., 2008) in addition to serving as a natural habitat for local flora and fauna (Prochnow., et al., 2009); Common grass can be cultivated in areas not currently being used for food production, thereby avoiding the ‘Food vs. Fuel’ conflict (Sexton, Rajagopal, Ziberman, & Hochman, 2008); Permanent grassland is not ploughed and will protect against soil erosion and contribute to ground water formation (Prochnow., et al., 2009); Common grass is perennial and does not need to be reseeded each year, thus saving energy (Uellendahl, et al., 2008); Common grass can be used cyclically, harnessing CO_2 from the atmosphere for plant growth and potentially reducing overall greenhouse gas emissions (Prochnow., et al., 2009); Common grass can and is being used successfully in co-digestion processes, with biogas yields comparable to those of maize and other energy crops (Uellendahl, et al., 2008) (Twidell & Weir, 2006) (Prochnow., et al., 2009).

Despite the potential benefits of using common grass in an anaerobic digestion process, to the author's knowledge, current literature is incomplete regarding the (P)EROI, environmental impact, GWP 100 and overall sustainability of utilizing common grass mixed with cow manure in a co-digestion process. It is unclear how much material and energy is required to grow, harvest, transport and process common grasses for use in an anaerobic digester. While it has been established that biogas production from biomass is possible, it is unclear whether or not this process can be done in an environmentally sustainable manner.

1.1.1 ... Research Aims

The question that this study would like to address is whether or not (and under which circumstances) a digester can produce biogas for the gas grid with a net gain in energy and a minimal environmental impact when using common grass and cow manure in a co-digestion process. The primary goal of this research is to develop a materials and energy flow analysis (MEFA) of the biogas production process and perform a Life Cycle Analysis (LCA) of biogas produced from common grass and cow manure. The results of this LCA will indicate the environmental impact, (P)EROI and GWP of the biogas production process. By studying real-world data from existing installations and performing a realistic case study, this study will determine the impacts and sustainability of a biogas production process utilizing common grass and cow manure as a feedstock.

1.1.2 ... Flexigas Project

In order to meet European Union 2020 emission targets, the Dutch government has set a target of replacing four billion cubic meters of natural gas annually with biogas by the year 2020 (Flexigas, 2013). To help initiate this development, the Dutch government has funded the Flexigas project, which aims to support decentralized biogas production.

The Flexigas project is led by RenQi and is composed of eleven companies, six research institutes and two other organisations. Working together, these groups cover several broad topics related to the development of a smart biogas grid within the Netherlands. Areas of study include: The optimisation and management of the smart biogas grid; Qualitative and quantitative control of the biogas production process; Biogas conversion (reprocessing, transport and storage); Biogas applications; Research, educational courses, work placements and undergraduate research projects.

The research project "Sustainability of biogas production from biomass waste streams: Grass and cow manure co-digestion process" falls under the heading of 'Work Package A: The optimisation and management of the smart biogas grid' (Flexigas, 2013). This project is a joint effort between the Hanze University of Applied Science and TNO, the Netherlands Organisation for Applied Scientific Research. This project aims to optimise the integration of a smart biogas grid. Specifically, this project will encourage local, sustainable biogas production by developing an interactive, dynamic software package which can determine the effectiveness and impact of any proposed biogas facility by employing several indicators, such as the (P)EROI, environmental impact and GWP (Pierie, Moll, van Gemert, & Benders, 2012). This study will contribute towards the goals of the Flexigas project by investigating the biogas potential and indicators associated with exploiting common grasses within the north-east Netherlands as a feedstock. The excel-based biogas production model developed as part of this study will provide the basis for the more user-friendly, interactive geographic model being produced by TNO. This research will help enable the design of future biogas installations, and indicate the sustainability of using common grass as a feedstock therein.

1.1.3 ... Outline of Report

This paper will begin with a discussion of the methodology used to perform the LCA of biogas in *Section 2 - State of the Art of Life Cycle Analysis*. This is followed by a detailed description of the biogas production model which was developed in *Section 3 - Biogas Production Model*. A case study is then considered as a basis for evaluating the practical application of the biogas production model, discussed in *Section 4 - Case Study: Potential for producing biogas from common grass in the village of Hoogkerk*. The results of this case study are presented in *Section 5 - Results comparing biogas production from common grass with alternate energy production*. An evaluation of the performance of the biogas production model is performed in *Section 6 - Evaluation of the Biogas Production Model*. A discussion of the implications of the results obtained from the biogas production model is performed in *Section 7 - Discussion of LCA Results*. Finally, conclusions are presented regarding the outcomes of this project in *Section 8 - Conclusions*.

2 State of the Art of Life Cycle Analysis

A life cycle analysis is the study of the overall impact of a particular product or process. Specifically, it is an account of the materials and energy required to produce a particular product. In this study, the product in question is biogas. The primary goal of an LCA is to determine a product's impact on human health and the environment (Pré, 2008). Impacts are quantified in terms of indicators. In this study, (P)EROI, GWP and Eco Points are the primary indicators examined and are explained in *Section 2.1.2*. LCA is widely used within literature to compare and evaluate the impact of different processes and products. The advantage of an LCA is that we can quantify abstract concepts, such as environmental impact. By performing a comparative LCA, two related processes can be compared and their relative advantages and disadvantages (in terms of impact factors) can be determined. It is important to note that indicators have no inherent meaning, but must be compared to another process in order to determine their relative impact. In this study, biogas production from grass is compared with biogas production from intensively produced maize or from municipal organic household waste, as well as natural gas production.

2.1 LCA Modeling with SimaPro

In this study, the LCA computer program SimaPro has been used to determine the impact factors of the biogas production process. SimaPro uses established data to account for the direct and indirect impacts of production processes. Direct impacts account for the energy and materials which are consumed on-site during the biogas production process (for instance, consuming electricity to operate pumps). Indirect impacts account for the materials and/or energy required to produce the materials and energy consumed on-site during the biogas production process (for instance, the off-site production of electricity which will later be consumed on-site). Material and energy consumption, as well as emissions and their impacts, are tracked over the entire lifetime (from production to use to disposal) of a given product or process. By linking these data together, a more complex process (such as the biogas production process) can be modelled and analyzed, as discussed in *Section 3 - Biogas Production Model*.

2.1.1 ... Materials and Energy Flow Analysis

All processes consist of materials and energy inputs and outputs. Taking account of these flows is known as a materials and energy flow analysis, or MEFA. MEFA allows us to track the materials and energy invested in and produced by any particular operation. The biogas production model developed during this study is essentially an application which tracks materials and energy flow through the biogas production chain and records the impacts of each process step. MEFA is the basis for the biogas production model's design and some form of MEFA is an essential step in any LCA.

2.1.2 ... Impact Factors

Impact factors show the results of an LCA in terms of indicators which can be easily compared with other processes. In this study, indicators quantify the impacts of material and energy flow associated with biogas production. Specifically, (P)EROI, GWP 100 and Eco Points are examined to provide an indication of the sustainability of a process. Both direct and indirect impact categories are comparable and contribute to the overall impact of the biogas production process; they are distinguished by whether their impacts occur within or without the system being studied.

2.1.3 ... Process Energy Return On Investment

The Process Energy Return On Energy Investment, or (P)EROI, is the amount of energy generated from a process compared to amount of energy used to run this process (Hall., Balogh, & Murphy, 2009). (P)EROI provides a clear indication of the effectiveness and net energy gain (or loss) of any energy production process. Ideally, an energy production process with an (P)EROI greater than 1:1 should be viable, although it has been argued that a minimum (P)EROI of 1.3:1 is required in order to account for material and energy inputs which are omitted from LCA studies (Hall & Klitgaard, 2012). It has further been argued that a minimum (P)EROI of 3:1 is required for energy production processes in order to maintain our current standard of living and account for environmental impacts (Hall., Balogh, & Murphy, 2009).

2.1.4 ... Global Warming Potential

Global warming potential, commonly referred to as carbon footprint, is the contributing effect of various process emissions on global warming. GWP represents a gaseous compound's atmospheric lifetime and light scattering ability relative to that of carbon dioxide over a 20, 50, 100 or 500 year period (IPCC, 2007). The influence of different greenhouse gases is normalized against carbon dioxide and expressed in terms of kilograms of carbon dioxide equivalent (kgCO_2eq). The GWP of common emissions is summarized in *Table 2.1.4.1 - GWP for various emissions*.

Table 2.1.4.1 - GWP for various emissions

Common Name	**Chemical Formula**	**GWP for 100 year time horizon (kgCO_2eq)** (IPCC, 2007)
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	298

In this study, the GWP for a 100 year time horizon (GWP 100) is employed. This indicator allows us to compare the GWP of biogas production with that of fossil fuels or other renewable energy technologies. The GWP of various emissions associated with the biogas production process can be found in *Appendix 11.2.12*.

2.1.5 ... Environmental Impact

The environmental impact of a given process can be difficult to measure in quantitative terms. This study employs the Eco-indicator 99 methodology, which is a weighted measurement system used by the LCA program SimaPro (Pré, 2008). Eco-indicator 99 tracks all emissions associated with a process and assigns a relative value to these in terms of Eco Points: the greater the impact of a given emission, the higher its Eco Point rating. The Eco-indicator 99 rating system is characterized by several end-point factors, particularly the damage to human health (measured in terms of emissions), the damage to ecosystem quality (measured in terms of emissions and land use) and the damage to resources (measured in terms of resource depletion) (Pré, 2008). This study focuses on environmental sustainability and employs the Eco-indicator 99 (E) indicator which measures damage to ecosystem quality.

2.1.6 ... Economic Impact

The primary goal of this study is to determine the environmental sustainability of biogas production. However, economics also play an important role in many business models. As such, the biogas production model contains some basic cost estimate information, which will be further developed at a later date. It should be noted that economic models can often be misleading: a form of energy production can be considered economically viable even if it does not achieve the desired environmental and social benefits. One of the goals of this research is to highlight the importance of other indicators by placing social and environmental impacts before economic benefits. However, a basic economic analysis is included to reflect its social importance, despite the potentially conflicting nature of economics and environmental sustainability.

2.2 Defining Sustainability in LCA

The primary goal of this study is to define the sustainability of biogas production from a grass and cow manure co-digestion process. Sustainability can be defined as ‘‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’’ (World Commission on Environment and Development, 1987). Sustainability is a broad concept which incorporates everything from environmental impacts to economics to social structures (Soini & Birkeland, 2014). While this project does not delve deeply into social or economic sustainability, it does attempt to measure the environmental sustainability (in terms of Eco Points and GWP) as well as the renewability (in terms of (P)EROI) of the biogas production process.

It bears explaining how the indicators chosen for this study reflect the sustainability of the biogas production process. (P)EROI represents the amount of net energy gained from an energy production process. An energy production process with (P)EROI of less than 1:1 (arguably, even less than 1.3:1) consumes more energy than it produces, and therefore is not considered a renewable energy source. So long as biogas production has a return of greater than 1.3:1, it can be said to be a renewable resource in that continuing the process will continue to provide a net gain in energy.

Environmental impact and GWP are interpreted differently: Both of these indicators reflect negative environmental impact, although GWP specifically addresses the issue of global warming. In both cases, the lower the impact of a process, the more sustainable it is. That is, a process with a relatively low impact can be operated for a longer time than a process with a relatively high impact, while having the same overall impact. Environmental impact and GWP do not indicate absolute sustainability, only the relative sustainability between different processes which are compared.

Finally, economic renewability is touched on and indicates the financial gains of a process compared to the investments. Similar to (P)EROI (except that we consider finances in place of energy), economic renewability indicates whether a process can cover its operating costs in a free market environment independently or must be subsidised. Since economics is not the main focus of this study, the term “sustainability” in this report refers explicitly to environmental sustainability, not economic impacts, which are considered separately.

2.3 LCA Boundaries

It is important to note that the focus of this LCA is on gas production, not consumption. The energy and material inputs for this LCA are only considered for the biogas production steps, as described in *Section 4.3 - Biogas Production Chain Sub-module Descriptions*. Further, it has been assumed that once gas is injected into a gas grid, its behaviour will not deviate from gas produced by another method. Therefore, this LCA does not consider the end use of the gas being produced, nor the end use of heat and electricity produced in the case of CHP utilization.

The exception to this rule is when considering the LCA of natural gas production compared to biogas production. One large motivator for developing biogas technologies is to reduce greenhouse gas emissions released by fossil fuel use. The largest portion of emissions from natural gas production (roughly 75%) comes from the actual combustion of the gas, where non-biogenic carbon is released into the atmosphere (Pré, SimaPro Ecoinvent Database, 2013). In contrast, when biogas is combusted, biogenic carbon is released into the atmosphere. Unlike non-biogenic carbon released from fossil fuel combustion, biogenic carbon is considered to be taken up by new plant growth in a continuous cycle. Therefore, all of the carbon within biomass which is converted into biogas and later combusted to form CO_2 will later be reabsorbed into biomass, so that net greenhouse gas emissions are considered to be zero (i.e. biogas is considered to be carbon neutral). There are still emissions from biogas production due to energy and material inputs, but these are accounted for during the LCA of the production process. In contrast, emissions from natural gas combustion are not considered to be "trapped" in a continuous cycle, but to contribute in full to carbon levels in the atmosphere. Since biogas production intends to offset these emissions, it is important to consider the end use of natural gas. Therefore, when comparing biogas to natural gas production in terms of GWP and environmental impact, the emissions from natural gas combustion are considered, but the emissions from biogas combustion are omitted. In this study, it is assumed that all offset natural gas is combusted and emitted to the atmosphere, not fixed in organic materials.

This LCA is currently limited to the north-east region of the Netherlands and focuses primarily on the use of common grass and cow manure in a co-digestion process in small-scale biogas production facilities. The varieties of grass studied are a mixture of species typical of this area. The biogas facility design in this LCA is that typically found in the Netherlands: specifically, a mesophilic wet reactor design has been modeled.

3 Biogas Production Model

To analyze the biogas production chain, the process has been divided into several interlinked sub-modules which can be analyzed independently. These sub-modules are simulated in the LCA-program SimaPro and compiled in the Excel-based biogas production model, as proposed by (Pierie, Moll, van Gemert, & Benders, 2012). *Figure 2.1.6.1 - Biogas production chain* indicates the overall biogas production process and the interactions of the various sub-modules which have been modelled. Materials and energy inputs are required to drive the biogas production process wherein grass and cow manure are harvested and transported on-site to be digested. The resulting biogas can be utilized off-site, while digestate can be returned to the biomass source to maintain a sustainable nutrient cycle. System boundaries and sub-module descriptions are provided in *Section 4.3 - Sub-module Descriptions*.

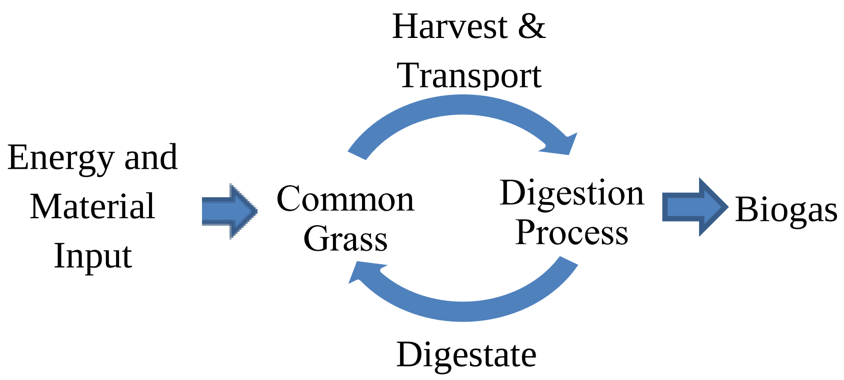


Figure 2.1.6.1 - Biogas production chain

The biogas production model simulates the materials and energy flow (MEFA) of each sub-module using the concept of industrial metabolism, which aims to account for the materials and energy utilization of human behaviours (Haberl & Weisz, 2007). Each sub-module of the biogas production model can be described by several components, as described by (Pierie, Moll, van Gemert, & Benders, 2012) and shown below in *Figure 2.1.6.2 - Structure of a single sub-module based on dynamic MEFA / LCA* . Primary flows are the material and energy inputs directly required for the production of biogas, as well as the final outputs and by-products. In this case, grass and cow manure are the primary inputs; biogas is the primary output; digestate and emissions are the primary by-products (although digestate is generally assumed to be recycled within the process). For each sub-module, several indicators (or impact factors) have been determined which indicate the relative environmental and health impacts of each stage of the biogas production process. Specifically, (P)EROI, GWP and Eco Points are examined, although other indicators can easily be incorporated into the model if desired. The cumulative effects of all sub-modules are then compared to other methods of gas production. The article 'Researching and modelling energy efficiency, sustainability and flexibility of biogas chains' (Pierie, Moll, van Gemert, & Benders, 2012) provides further information about the methodology behind the biogas production model design.

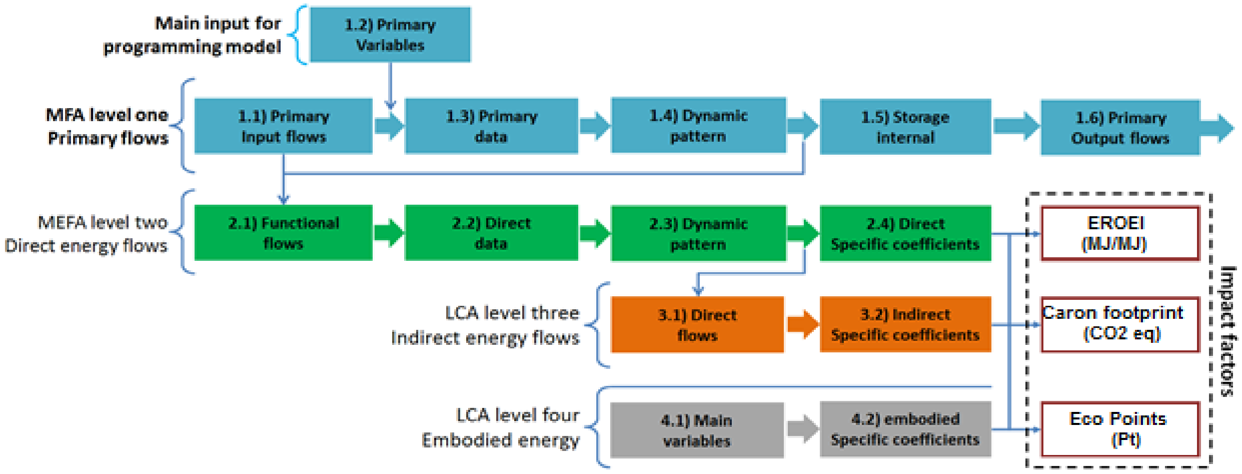


Figure 2.1.6.2 - Structure of a single sub-module based on dynamic MEFA / LCA (Pierie, Moll, van Gemert, & Benders, 2012)

The biogas production model is unique in that it tracks the energy consumption, GWP and environmental impact of each component process separately. This approach allows the simplification of the MEFA of biogas production while also allowing for easy modification in order to determine the impacts of biogas production for local conditions. The biogas production model is therefore flexible and can be easily modified to model a particular scenario. Having a model which can be easily adapted to different conditions is essential if it is to be used to ascertain the viability of future biogas production facilities. In addition, the use of excel as the basis for the model is important: Excel is commonly available and generally well understood, allowing for public use of the model; Excel is a transparent program, meaning that it is easy to track data and calculations and no information is hidden from the public. *Appendix 11.5* is a copy of the biogas production model user's manual which describes in detail the layout and controls of the model.

4 Case Study: Potential for producing biogas from common grass in the village of Hoogkerk

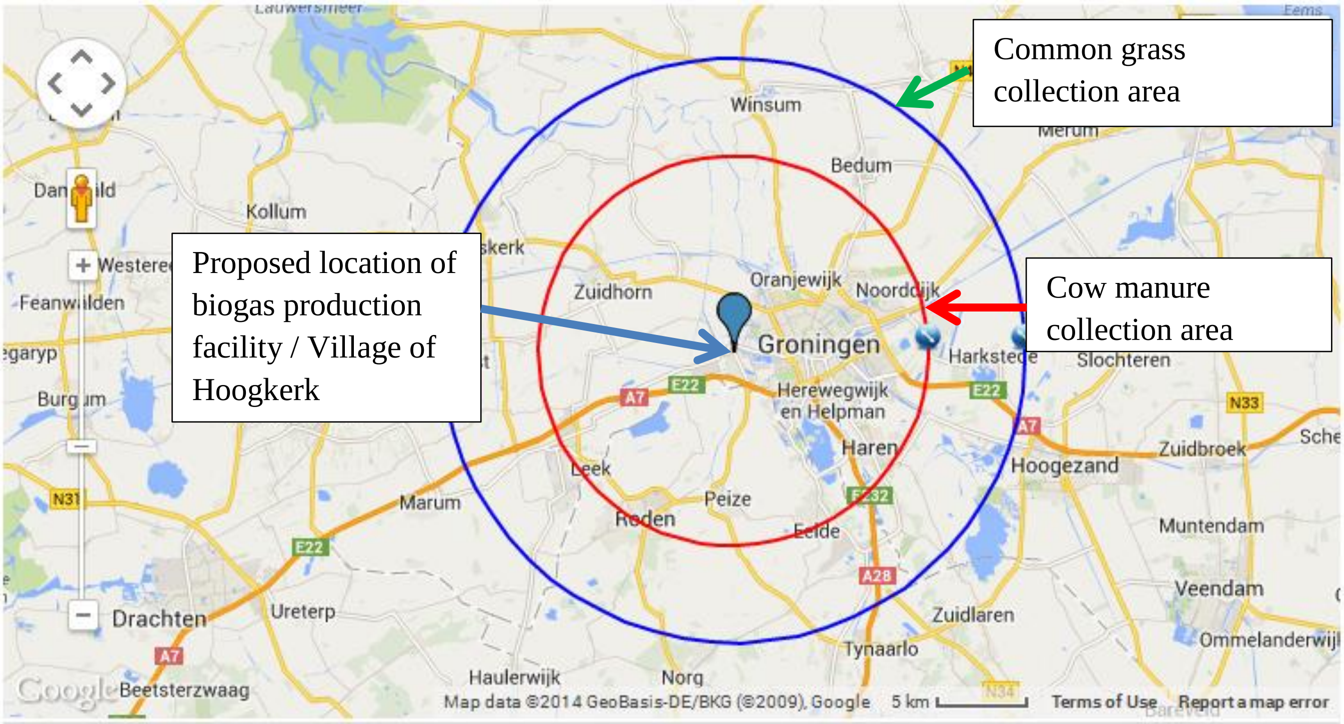
In order to demonstrate the function of the biogas production model, a case study has been performed in village of Hoogkerk and surroundings in the north-east Netherlands. This scenario models the implementation of a biogas production process (utilizing common grass and cow manure) in order to meet a portion of the energy demands of the village of Hoogkerk. This scenario provides a basis to which alternate energy production scenarios can be compared.

4.1 Case Study Description

The village of Hoogkerk in the Netherlands has a population of 15,750, and approximately 5,950 households (Wikipedia).The average household in the Netherlands consumes between 1,900 and 2,200 m^3 of gas per year (Brounen, Kok, & Quigley, 2011) (Meirmans, 2013). Based on this knowledge, Hoogkerk will consume between 11 and 13 million Nm^3 of gas per year. In addition, the average household in the Netherlands consumes 3,600 kWh of electricity per year (Brounen, Kok, & Quigley, 2011), or 21,420 MWh of electricity for the village of Hoogkerk per year.

In the Netherlands, it is typical that approximately 3.5% of total land area is designated a natural area, 12.8% of total land area is considered artificial (of which an unspecified portion is considered vegetated, non-agricultural land) and 61.4% of total land area is considered agricultural (European Commission for Agriculture and Rural Development, 2013). In this case study, it is assumed that common grass for biogas production is acquired within a 15 km radius of Hoogkerk. It is assumed that 10% of total land area (a combination of nature, agricultural and vegetated non-agricultural land), or 7,068 ha, consists of common grass which will be used for biogas production. Cow manure is acquired within a 10 km radius of Hoogkerk. This area is represented in *Figure 2.1.6.1 - Area utilized to provide Hoogkerk with biogas*.

Figure 2.1.6.1 - Area utilized to provide Hoogkerk with biogas



4.1.1 ... Biogas Production Process Design

By cooperating with the Biomass Technology Group BV "Biogas uit natuurgas" project and the V.O.F. Lammertink biogas facility (Reumerman, 2013), real world data has been obtained. This data provides realistic information about the methods and energy used when using common grass as a feedstock for biogas production. This data also serves as a reference for determining biogas yields of common grass in non-ideal conditions, in a working biogas facility. The biogas production process in this case study is modeled on the mesophilic wet reactor design found at the V.O.F. Lammertink biogas facility. A detailed overview of the process chain is provided below, in *Section 4.3 - Biogas Production Chain Sub-module Descriptions.*

4.1.2 ... Laboratory Studies of Biomass Properties

Upon request, the Life Science and Technology Department at Hanze University of Applies Science conducted several experiments to measure the biogas potential of common grass mixed with cow manure. Some tests were performed with pre-treated grass and others with non-pre-treated grass. The Chamber of Agriculture of Lower Saxony (LWK Nds.) - German DELaND subproject, has also provided information on the biogas potential of grass from landscape management in north-west Germany. The results of these studies are indicative of the biogas potential of common grass species found in the north-east Netherlands. These studies serve as justification and act as the basis for the properties assumed for the grass feedstock in this case study.

4.1.3 ... Case Study Assumptions and Parameters

In the Hoogkerk case study, several assumptions are made. These are summarized in *Table 4.1.3.1 - Case study assumptions and parameters* and explained in further detail in the sub-module descriptions in *Section 4.3*.

Table 4.1.3.1 - Case study assumptions and parameters

Variable	Assumed Value	Source
Annual grass yield	14,286 kg_{FM} ha^{-1}	(Gerin, Vliegen, & Jossart, 2008)
Dry matter content of grass upon collection	35%	(Fubbeker & Muller, 2003) (Gordon, Patterson, Porter, & Unsworth, 2000)
ODM fraction of DM	90%	(Smyth, Murphy, & O'Brien, 2009)
Cost of grass	0 – 36 € ton^{-1}_{FM} (36 € ton^{-1}_{FM} on average)	(Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011)
Transportation distance of grass	11 km (15 km maximum)	N.A.
Transportation distance of manure	7.5 km (10 km maximum)	N.A.
Pre-treatment of grass?	Yes	N.A.
Biogas potential grass	0.446 L kg_{ODM}^{-1}	(Reumerman, 2013)
Biogas potential cow manure	0.300 L kg_{ODM}^{-1}	(Wageningen UR Livestock Research, 2013)
Biogas methane content	55%	(Reumerman, 2013)
Digestate returned to field?	Yes	N.A.

Further, it is assumed that all biogas produced will be upgraded and injected into the gas grid to offset natural gas use. Based on these assumptions and the scenario details provided above, it should be possible for the village of Hoogkerk to provide approximately one half of their gas needs from biogas production from common grass and cow manure. The impacts of this scenario were calculated using the biogas production model and are presented in *Section 5 - Results comparing biogas production from common grass with alternate energy production*.

4.2 Comparative LCA: Alternate energy production scenarios

In order to evaluate the effectiveness and relative sustainability of biogas production from grass, several alternate energy scenarios must developed for the village of Hoogkerk. In this case study, three common alternate gas production methods are analyzed: biogas production from intensively farmed maize, biogas production from municipal organic household waste (considering impacts only after waste disposal) and natural gas production.

Two alternate scenarios are examined for the end use of biogas: First, biogas can be injected into a gas grid and transported to consumers. Alternately, biogas can be combusted on-site for heat and electricity generation by a CHP unit. These scenarios are described in further detail below. In addition, some operating parameters of the biogas production process are altered in order to demonstrate their impact and/or usefulness. Specifically, the effects of pre-treatment, variable transportation distance and variable feedstock cost are all considered.

For comparison, similar production chains have been modelled for the collection and processing of alternate biomass feedstocks, specifically maize produced intensively and municipal organic household waste. The impacts of these alternate feedstocks are noted in *Appendix 11.2.7* and *11.2.8*, respectively, and are credited to the project supervisor, Frank Pierie, PhD. Researcher at HanzeResearch – Energy. Detailed information regarding these alternate feedstocks is not discussed here, since it is outside the scope of this study. Biogas produced from common grass is also compared to natural gas production. The impacts of natural gas production are recorded in *Appendix 11.2.9*.

From this study, the relative impacts of producing biogas from grass in the village of Hoogkerk have been examined. Each method of gas production shows a range of impacts associated with the uncertainty of the primary inputs: *Table 11.1.4.1 - Variable primary inputs*, in *Appendix 11.1.4*, details the primary inputs which have been varied in this study, noting the average, minimum and maximum values used.

4.3 Biogas Production Chain Sub-module Descriptions

Biogas production begins with the cutting and collection of common grass. Once cut, the grass must be transported to the biogas facility. There, the grass is ensiled for some time before being pre-treated and mixed with cow manure in the digester. The grass/manure slurry is heated and mixed in an anaerobic environment, producing biogas and digestate. Biogas can be upgraded and injected into a gas grid. Digestate can be returned to the field as an organic fertilizer or disposed of off-site. This process chain is broken down into interlinked sub-modules, as shown in *Figure 4.1.3.1 - Process steps for feedstock collection and processing* and described in detail below. The impacts of each sub-module are recorded in *Appendix 11.2*.

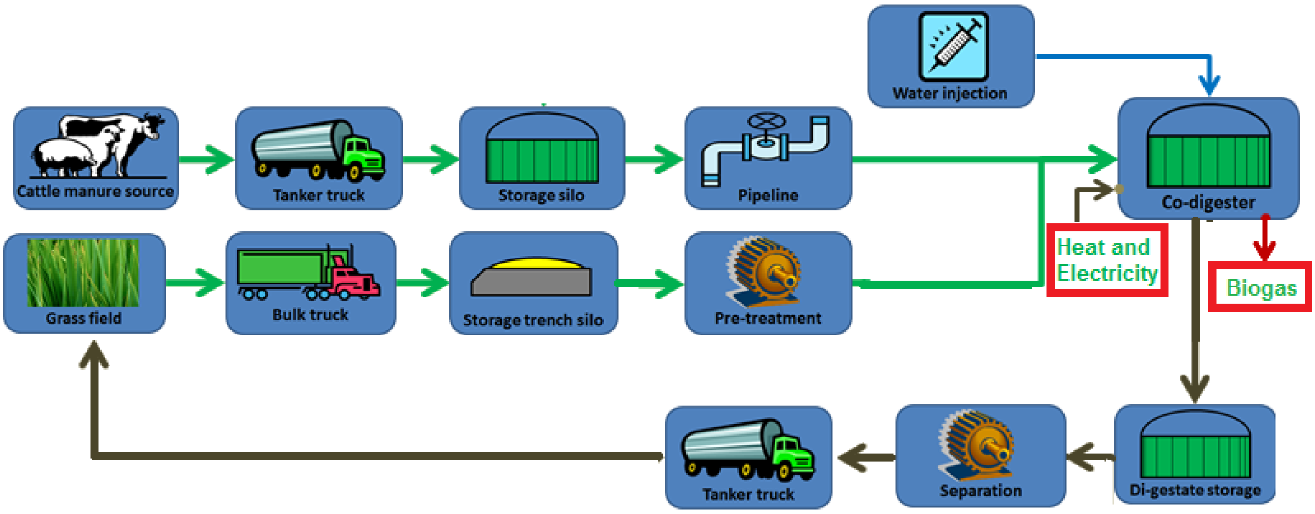


Figure 4.1.3.1 - Process steps for feedstock collection and processing

4.3.1 ... Grass Harvesting

The biogas production process begins with harvesting biomass for the digester. Grass harvesting consists of several steps:

1) Transport of Equipment – Agricultural equipment must be transported to the site containing the biomass.
2) Grass Mowing – Depending on agricultural practices, grass will typically be cut one to four times per year. Yields vary significantly depending on location and species of grass, as well as time of harvest.
3) Grass Tedding – Tedding allows the grass to be dried on the field, increasing the relative dry matter content and reducing the amount of non-volatile organic mass (i.e. water) which must be transported. This step is not necessarily performed.
4) Grass Swathing – Swathing is the process of piling the grass into windrows, allowing for easier collection. This step is not necessarily performed.
5) Grass Collection and Loading for Transport – Grass must be picked up and loaded for transport to the biogas facility.

The Energy Invested, GWP and environmental impact of harvesting grass is found in *Appendix 11.2.1*. *Appendix 11.3.1* details the embodied energy associated with harvesting grass.

Economic impact is also considered: In a study performed by (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011), the cost of grass silage production from landscape management was found to be between 31.2 and 39.3 € ton_{FM}^{-1}. The variations in cost are largely the result of seasonal variations in biomass yields. A similar cost for grass is reported by (Wageningen UR Livestock Research, 2013), which quotes a cost of 521 € ha^{-1} and 0.156 € kg_{DM}^{-1}, which is equivalent to a cost of between 36.50 and 54.60 € ton_{FM}^{-1} for grass produced from landscape management. For comparison, maize silage produced intensively was found to cost between 28 and 37 € ton_{FM}^{-1} (Bekkering, Broekhuis, & van Gemert, 2010) (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011).

In this case study, the cost of grass is assumed to be 36 € ton_{FM}^{-1}; the cost of maize is assumed to be 35 € ton_{FM}^{-1}; the cost of organic waste is assumed to be nil. Notably, in certain situations, it may be possible to receive money for disposing of waste grass from landscape management. This possibility is discussed in *Section 5.1.5 - Economic impact of various energy production* and *Section 7.1.4 - Economic costs of alternate energy production.*

4.3.2 ... Grass Transport and Storage

Grass is typically transported by truck. Distance and tonnage of grass are consequently the primary variables which affect the impacts of truck transport. Therefore, truck transport impacts are measured in terms of tons.km for both loaded hauls and empty hauls. *Table 11.2.2.1 - Impacts of truck transport* in *Appendix 11.2.2* details the impacts of truck transport.

Typically, organic material is ensiled in order to preserve the biomass throughout the winter when there is no fresh biomass available. Proper ensiling has the additional benefit of breaking up strong lignin and cellulose bonds within the biomass, increasing the potential methane yields within the digester (Ambye-Jensen, Johansen, Didion, Kadar, Schmidt, & Meyer, 2013). However, biomass also loses some organic matter while it is being ensiled due to natural decomposition processes. Amounts of organic matter losses are largely dependent on ensiling time and the water content of the biomass: Organic matter losses are generally higher with higher moisture content and longer ensiling times (Yahaya, Kawai, Takahashi, & Matsuoka, 2001) (Kennedy & Griffeth, 1959). The embodied energy of the silage storage facilities is detailed in *Appendix 11.3.2*. Expected losses during ensiling are discussed in *Section 4.3.9 - Losses*.

In order to move grass into and out of storage, a front end loader is typically used. Impacts are measured per ton.km and are summarised in *Table 11.2.2.2 – Impacts of front-end loader use*, in *Appendix 11.2.2*.

4.3.3 ... Grass Pre-treatment

It has been shown that pre-treating grass by ensiling, mulching or wet oxidation can improve biogas yields (Uellendahl, et al., 2008) (Reumerman, 2013). The potential costs and benefits of such a process are discussed in *Section 5.3 - Impacts of the* pre-treatment. In this study, it was assumed that a hammer mill was used to mulch grass before being loaded into the digester, as at the V.O.F. Lammertink biogas facility (Reumerman, 2013). The hammer mill considered is electrically powered and constructed by Huning Maschinenbau GmbH. The impacts of pre-treatment are described in *Table 11.2.3.1 - Impacts of grass pre-treatment*, in *Appendix 11.2.3*.

4.3.4 ... Cow Manure

In the Netherlands, biogas facilities typically use a 1:1 mixture of cow manure and another source of biomass as a feedstock. Cow manure has a relatively low biogas potential, although it does offer three key benefits: 1) Cow manure contains the micro-organisms essential for the anaerobic digestion process (Twidell & Weir, 2006). 2) Cow manure acts as a pH buffer, maintaining a relatively constant acidity within the digester and protecting bacteria from sudden changes in their environment (Twidell & Weir, 2006). 3) Manure has relatively high water content, and helps to reduce the viscosity of the biomass slurry. The importance of reducing viscosity is discussed in *Section 4.3.5* below. In addition, Dutch law requires that commercial digesters use a substrate with a minimum of 50% cow manure if the resultant digestate is to be used as an organic fertilizer (Bekkering, Broekhuis, & van Gemert, 2010).

Due to its low biogas potential, it is not energetically efficient (in terms of (P)EROI) to transport cow manure over large distances. Instead, it is generally preferable to construct a biogas facility near to cow stables, where cow manure is readily available and easily transported to the digester. Manure, which is primarily liquid, can easily be stored on-site and transported by pump. Since it is required by law for manure to be properly treated and disposed of, it is possible for biogas facilities to receive approximately 15 € ton^{-1} of manure they collect (Bekkering, Broekhuis, & van Gemert, 2010).

4.3.5 ... Digestion Process

In order to extract biogas from a grass/manure mixture, the slurry must be heated, mixed, possibly diluted with water and retained in the digester for an ideal amount of time for bacteria to convert volatile organic dry matter into methane and other gases. For a mesophilic single-stage wet digestion processes typical in the Netherlands, retention times range from 15 to 30 days and operating temperatures range from 30 to 38˚C (Appels, Baeyens, Degreve, & Dewil, 2008). The biogas facility is sized in order to reflect the slurry flow rate and desired retention time. The energy impacts for mixing and heating the substrate are accounted for in *Appendix 11.2.3*. The embodied energy of the biogas facility is accounted for in *Appendix 11.3.3*.

During the co-digestion process, organic solids are digested by bacteria to produce biogas and digestate. For single-stage wet digesters, VS conversion rates range from 40 to 75% (Nizami & Murphy, 2010). In this study, an average VS conversion rate of 50% was assumed. A biogas potential of 0.446 L kg_{ODM}^{-1} is assumed for grass (Reumerman, 2013); a biogas potential of 0.300 L kg_{ODM}^{-1} is assumed for cow manure (Wageningen UR Livestock Research, 2013). The resultant biogas is assumed to have a methane content of 55 Vol% (Reumerman, 2013).

It is important that biomass be properly mixed and diluted before it can be processed in the digester. If the amount of dilution water is too low, the biogas plant may cease to function entirely due to clogging and layer formation. As such, dilution water may be required to obtain the desired slurry fluidity. A typical mesophilic single-stage wet digester in the

Netherlands is designed for a substrate with dry matter content of 8 to 30% (Jewell, Cummings, & Richards, 1993). In this study, a maximum dry matter content of 20% was assumed.

4.3.6 ... Gas Grid Injection

One option for utilizing biogas is to inject it into a gas grid for use off-site. This process is illustrated in *Figure 4.3.6.1 - Process steps for gas grid injection*. It is necessary to remove toxic and corrosive components from biogas before it can be utilized. Specifically, H_2S and ammonia must be filtered. It is also necessary to remove CO_2 from biogas to maintain a consistent energy content of gas in the grid. The impacts of filtering H_2S and ammonia and scrubbing CO_2 are summarized in *Appendix 11.2.4*. Biogas must then be compressed and transported to an injection point. This requires a compressor and pipeline infrastructure, as well as electricity consumption. The impacts of this procedure are summarized in *Appendix 11.2.4* and *11.3.4*.

Figure 4.3.6.1 - Process steps for gas grid injection

In this scenario, the LCA ends at the point of grid injection (with the exception of emissions from natural gas combustion, as discussed in *Section 2.3*). The justification for this is twofold: First, at the point of grid injection, all sources of gas (bio- or natural) are mixed and require the same energy inputs for further transport and use. Therefore, when performing a comparative LCA the additional impacts post-grid injection will be identical. Second, once gas is injected into a grid, its uses are many: Heat production (primarily), electricity production or a combination of these. Some industrial processes, such as $H_2$from steam reforming or nitrogen fertilizer production using the Haber-Bosch process are also possible. The off-site uses (and associated impacts) of biogas are highly variable and outside the scope of this study.

4.3.7 ... Combined Heat and Power

As an alternative to green gas injection into the gas grid, biogas can be combusted on-site in a CHP unit to produce electricity and heat. This process is illustrated in *Figure 4.3.7.1 - Process steps for CHP utilization*. Biogas must first be pre-filtered in order to remove corrosive and toxic elements such as H_2S and ammonia. The impacts of this process are identical to gas grid injection and are summarized in *Appendix 11.2.4*. Biogas can then be combusted on-site with a CHP unit. Notably, CO_2 does not need to be removed and biogas does not need to be compressed and transported before combustion, omitting several steps from the biogas production chain. CHP units typically have an electric efficiency of approximately 30%, meaning that 30% of the energy content of the biogas is converted to electricity while the rest is converted to heat. Heat recovery can be as high as 95% of heat produced (65% of total energy), although this rate can vary significantly (Thomas, 2013). This study assumes an average heat recovery of 50% (30% of total energy).

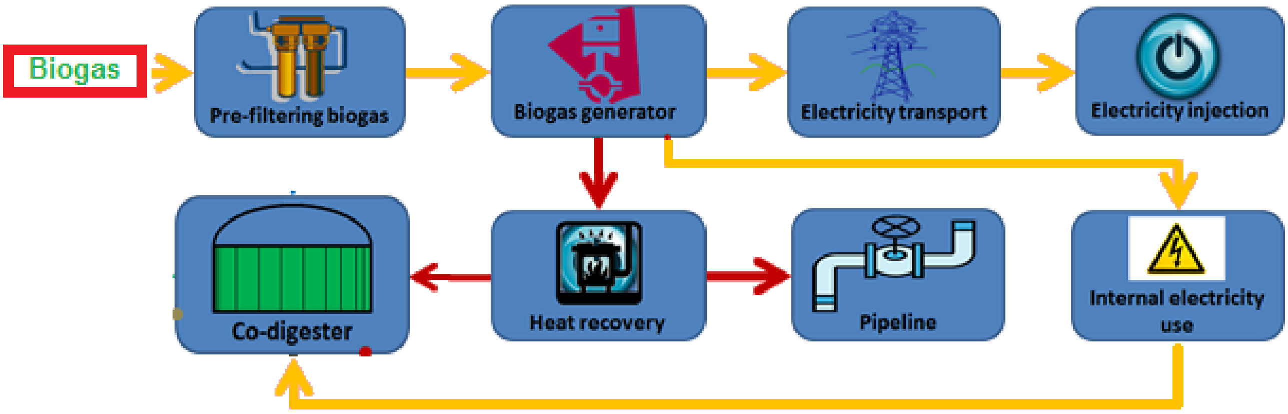


Figure 4.3.7.1 - Process steps for CHP utilization

A portion of the heat and electricity produced can be used to power the digester, substituting the consumption of heat and electricity from non-renewable sources. The impacts of this have been summarized in *Appendix 11.2.5* and *11.3.5*. The remainder of the heat produced by the CHP unit can be recovered and utilized in various ways, depending on local conditions: Heating greenhouses, district heating, Rankine cycle electricity production, adsorption chillers and other industrial processes are all possible applications of recovered heat from CHP units. Remaining electricity can be sold and injected into the electricity grid. This LCA does not consider the off-site uses of electricity and recovered heat which are highly variable and outside the scope of this study.

4.3.8 ... Digestate Treatment and Utilization

Digestate is one of the main by-products of the digestion process. Digestate is liquid slurry with a high nutrient content which can be used as an effective organic fertilizer. Digestate can be separated into thick and thin fractions, allowing for easier transport and distribution for various purposes (e.g. the thick fraction may be sold as compost while the thin fraction is used as a fertilizer on local fields). The volume required for digestate storage depends on slurry flow rate and storage time required.

Ideally, nutrient-rich slurry should be returned to its source (i.e. the source of the biomass) in order to maintain a sustainable nutrient cycle and reduce material and energy inputs in the form of chemical fertilizers. Additionally, anaerobically digested slurry has the advantages of increasing nitrogen availability by 10-20% and reducing ammonia losses by up to 70% through acidification, when compared with chemical fertilizers (Webb, et al., 2013). It is important to note that digestate must be spread over a relatively large area in order to achieve proper nutrient concentrations and to not lose excess nutrients due to surface runoff (Saam, Powell, Jackson-Smith, Bland, & Posner, 2005) (Gourley, Aarons, & Powell, 2012). Digestate use as fertilizer is not always possible or desirable. For example, digestate derived from household waste cannot necessarily be used on fields due to the potential hazard of heavy metal accumulation. In this case, digestate must be transported and disposed of in a waste treatment facility off-site. In any case, digestate is typically transported by truck. The impacts of digestate separation, storage, transportation, use and disposal are summarized in *Appendix 11.2.6* and *11.3.2*.

4.3.9 ... Losses

The biogas production process is a complex production chain with many process steps. At each step, some losses will occur. In this study it has been assumed that grass from landscape management has a loss of mass of 7% during harvest, due to drying. An additional loss of mass of 7% (20% of it DM) during silage production is also expected, resulting from natural decomposition processes (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011) (Kennedy & Griffeth, 1959). Throughout the biogas production process, losses have been assumed during many process steps, typically ranging from 0.1 to 2% (for mass losses) and 1 to 5% (for energy losses, particularly from heat transport and losses of biogas to the atmosphere). These numbers are typical assumptions found in literature and help to simulate a realistic biogas production scenario (Bekkering, Broekhuis, & van Gemert, 2010) (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011). *Table 4.3.9.1 - Losses during each process step* details the losses assumed for each sub-module of the biogas production process.

Table 4.3.9.1 - Losses during each process step

Process Step	Loss of Biomass (%)	Loss of Energy (%)
Grass Harvesting	2.0	0
Grass Transport	1.1	0
Grass Storage	5.0	0
Grass Pre-treatment	1.0	0
Cow Manure Collection & Storage	2.0	0
Digester Backup Boiler	0	5.0
Digestion Process	0.01	1.0
Pre-filtering Biogas (removal of H_2S and ammonia)	0	0.2
Biogas Upgrading (removal of CO_2)	0	0.4
Gas Grid Injection of Biogas	0	0.01
CHP Utilization	0	30
Electricity Transport to Grid	0	0.3
Heat Recovery and Transport to Grid	0	4.0
Digestate Treatment & Storage	1.02	0
Digestate Transport & Utilization	1.0	0

5 Results comparing biogas production from common grass with alternate energy production methods

The primary goal of this research is to determine the potential of biogas production from the co-digestion of grass with cow manure. Based on the Hoogkerk case study discussed in

Section 4, this proposed method of biogas production has been analyzed and compared with alternate energy production scenarios. The results of this analysis are presented below.

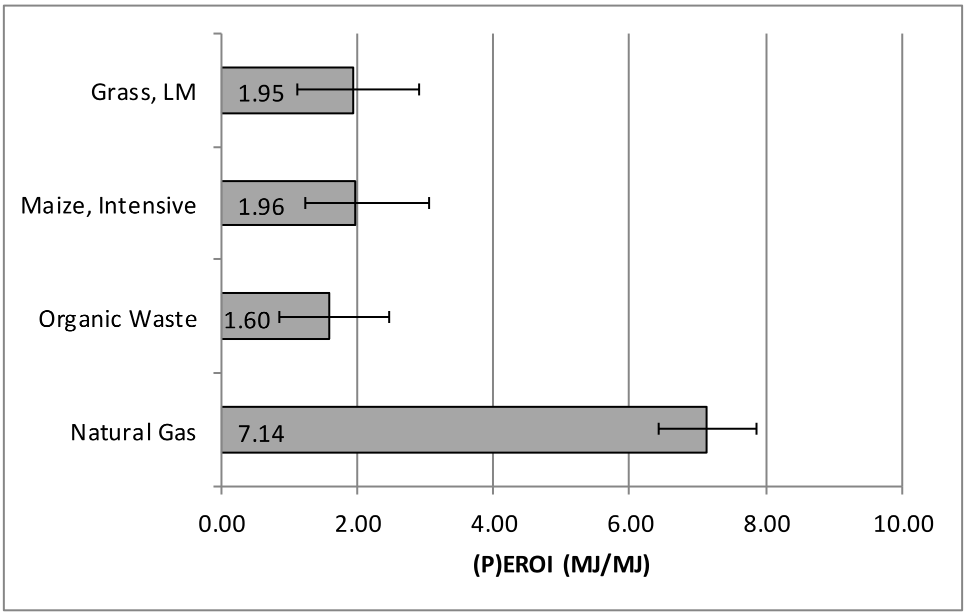
5.1.1 ... Normalization of Results

In order to compare the impacts of biogas produced from grass with those of biogas produced from maize, organic waste or even natural gas, the results must be normalized. In this case, the most indicative normalization factor is the amount of energy contained within the end product. Because the final gas product for every process studied is assumed to have the same energy content, all results are normalized per Nm^3 of gas produced. (P)EROI is not normalized, since this indicator is implicitly compared to the energy content of the end product of the energy production process.

5.1.2 ... (P)EROI of various energy production methods

Figure 5.1.2.1 - (P)EROI of various methods of energy production shows the potential (P)EROI for biogas produced from common grass, maize or organic waste, as well as natural gas. Notably, biogas produced from maize and grass is comparable, while natural gas has a significantly higher (P)EROI. Biogas produced from organic waste has a relatively low (P)EROI.

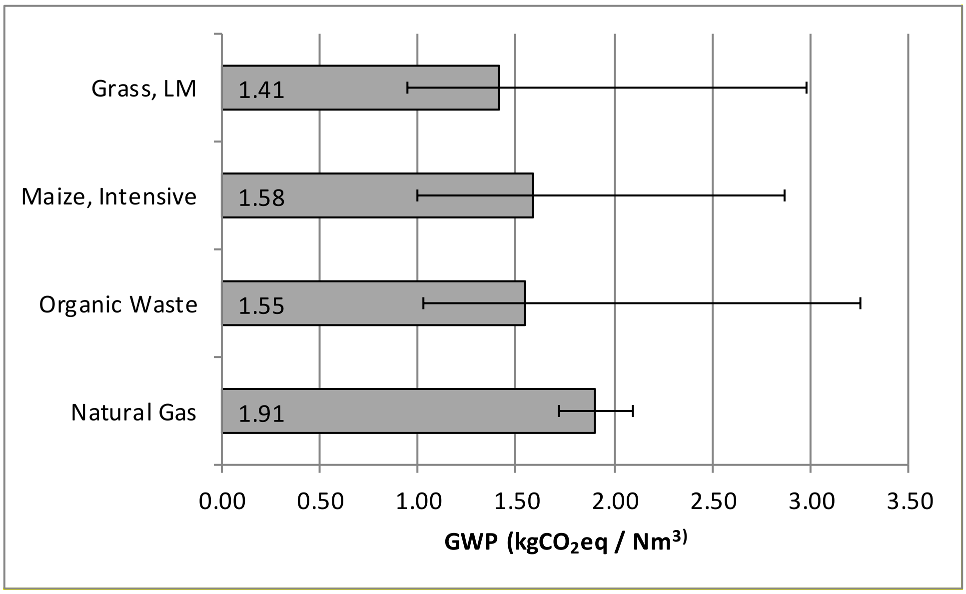
Figure 5.1.2.1 - (P)EROI of various methods of energy production



5.1.3 ... GWP of various energy production methods

The normalized GWP of one cubic meter of biogas produced from common grass, maize or organic waste, as well as natural gas, is shown in *Figure 5.1.3.1 – GWP of various methods of energy production*. The GWP of all biogas production methods on average are comparable, and notably lower than the GWP of natural gas production. However, all three biogas scenarios can potentially have a higher GWP than natural gas production, if the biogas production process is relatively intensive and biogas yields are relatively low.

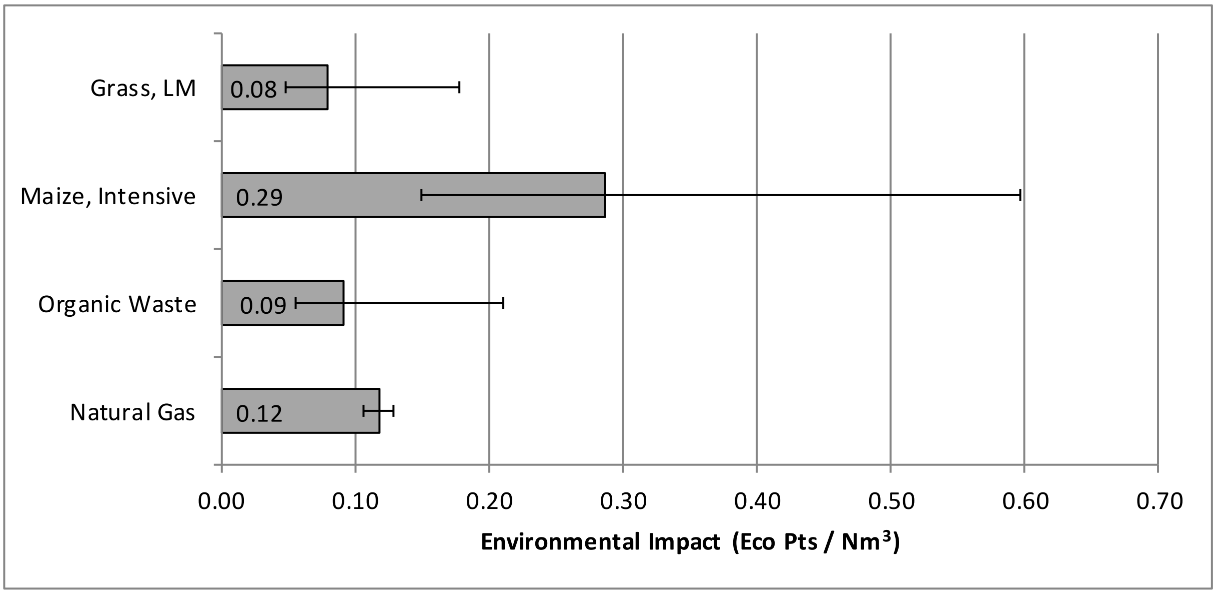
Figure 5.1.3.1 – GWP of various methods of energy production



5.1.4 ... Environmental impact of various energy production methods

The environmental impacts of biogas produced from common grass, maize and organic waste, as well as natural gas, are shown in *Figure 5.1.4.1 - Eco Points of various methods of energy production*. Here we see the potential benefit of using common grass, which has the lowest environmental impact of the four energy scenarios on average. However, as with GWP, environmental impacts for biogas produced from grass may be greater than those of natural gas if a relatively intensive production process is used. Notably, the environmental impact of biogas produced from maize is significantly higher than the other scenarios. This is likely the result of the greater land use impacts (including chemical fertilizer, pesticide and herbicide inputs) associated with the intensive production of maize. Biogas from organic waste has a low environmental impact on average, but like grass, it is possible for this impact to increase significantly.

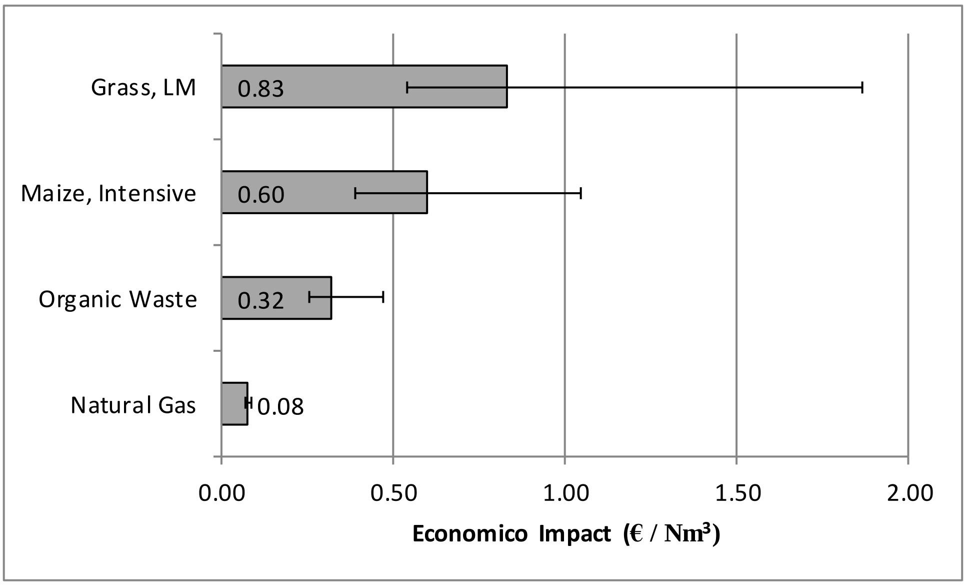
Figure 5.1.4.1 - Eco Points of various methods of energy production



5.1.5 ... Economic impact of various energy production methods

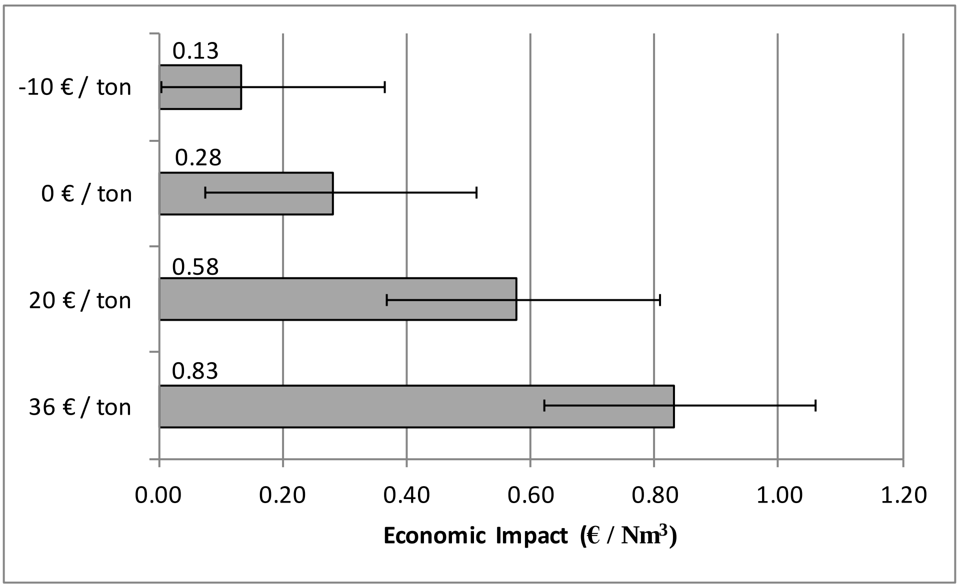
Economic analysis provides a guideline to show the relative economic costs of the different methods of gas production. *Figure 5.1.5.1 - Cost of producing one m3 of gas by various production methods* shows the relative cost of producing one cubic meter of gas by either natural gas production or biogas production using common grass, maize or organic waste. Notably, biogas production is not necessarily profitable without subsidies, and natural gas still provides a significantly higher profit margin than the alternate scenarios.

Figure 5.1.5.1 - Cost of producing one m^3 of gas by various production methods



The potential cost of biogas from grass appears significantly higher than other gas production methods. It must be noted that in this scenario, it was assumed that grass was purchased a market value of 36 € $ton^{-1}{}_{FM}$. However, it is possible that grass is obtained for free or even at a profit. The impact of this potential variation in the cost of grass is shown in *Figure 5.1.5.2 - Impact of variable cost of grass feedstock*. As shown, the costs of producing biogas from grass can be reduced dramatically (to the point of being negligible) as the cost of the feedstock decreases. The implications of this are discussed in further detail in *Section 7.1.4 - Economic costs of alternate energy production.*

Figure 5.1.5.2 - Impact of variable cost of grass feedstock



5.2 Impacts of grid injection of gas compared to CHP utilization

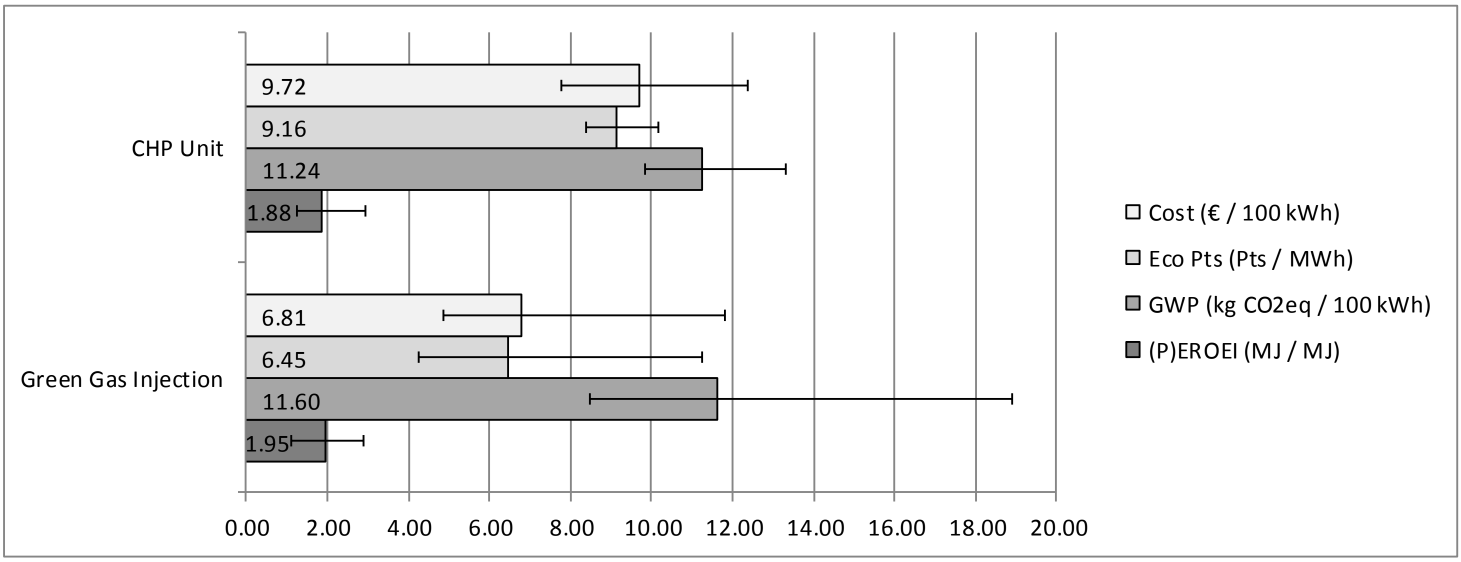
The production of grid-injected gas can be compared with on-site production of electricity and heat by combusting biogas in a CHP unit. When comparing grid-injected gas to heat and electricity production by CHP unit, impacts are normalized per MWh of recoverable energy produced.

Figure 5.1.5.1 – The relative impacts of grid-injected gas injection and CHP utilization shows the impacts of injecting green gas into the gas grid and on-site heat and electricity production utilizing a CHP unit. On average, it appears that utilizing a CHP unit has a higher environmental impact, and a lower GWP and (P)EROI. The cost of producing energy via CHP is higher per MWh, although one of the primary products, electricity, is also generally more highly valued than gas. As a result, while CHP units are more expensive to operate, the value of green electricity is typically such that operating a CHP unit is more profitable than injecting green gas into the gas grid. However, this observation largely depends on green energy subsidies, which are currently higher for green electricity than for green gas in terms of energy content.

In this scenario, it was assumed that heat and electricity produced by the CHP unit were partially used to power the biogas plant, thus offsetting the consumption of non-renewable resources. The impacts offset by using heat and electricity generated on-site to power the biogas production facility are summarized in *Appendix 11.2.11*. It was also assumed that the

CHP unit had an electrical conversion efficiency of 30% and that 50% of the heat produced by the CHP unit was recovered and used on-site and/or transported off-site. It is notable that as heat recovered from the CHP unit increases, the CHP scenario becomes increasingly viable. Similarly, if little to no heat is recovered from the CHP unit, grid-injected gas begins to show a relatively lower environmental impact and cost, and a higher (P)EROI.

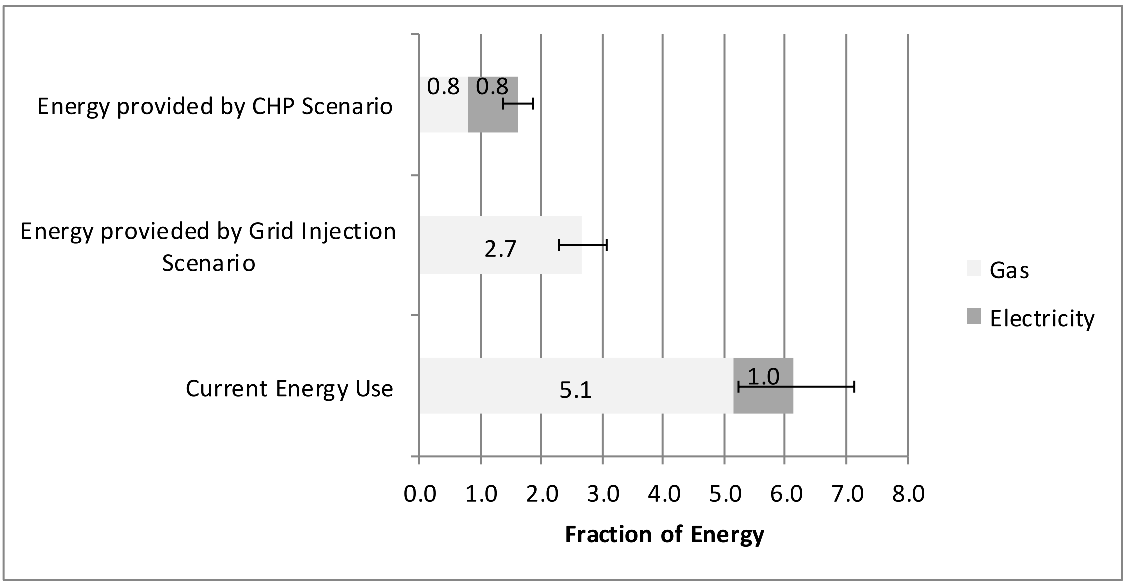
Figure 5.1.5.1 – The relative impacts of grid-injected gas injection and CHP utilization



5.2.1 ... Implications of CHP utilization for the village of Hoogkerk

The average household in the Netherlands consumes much more energy in the form of gas than electricity. This is demonstrated in *Figure 5.2.1.1 – Fraction of energy provided by CHP utilization compared to gas grid injection of biogas for the village of Hoogkerk*, where we see that gas accounts for roughly one sixth of total energy consumption. Looking at the two scenarios discussed, we see that injecting biogas into the gas grid can provide Hoogkerk with more than one half of their gas needs. If we assume that the heat recovered from the CHP unit is used for district heating of households, then CHP utilization can provide nearly all of Hoogkerk's electricity needs and offset approximately one fifth of their gas requirements. The ranges presented indicate the uncertainty of energy yields from biogas production, as well as uncertainty of household energy consumption in the Netherlands.

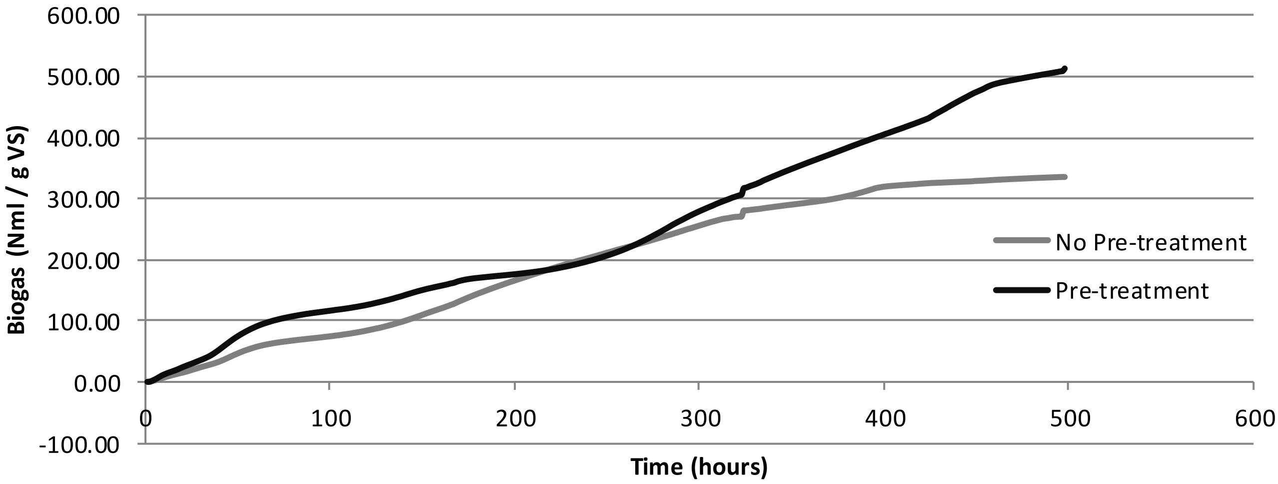
Figure 5.2.1.1 – Fraction of energy provided by CHP utilization compared to gas grid injection of biogas for the village of Hoogkerk



5.3 Impacts of the pre-treatment process

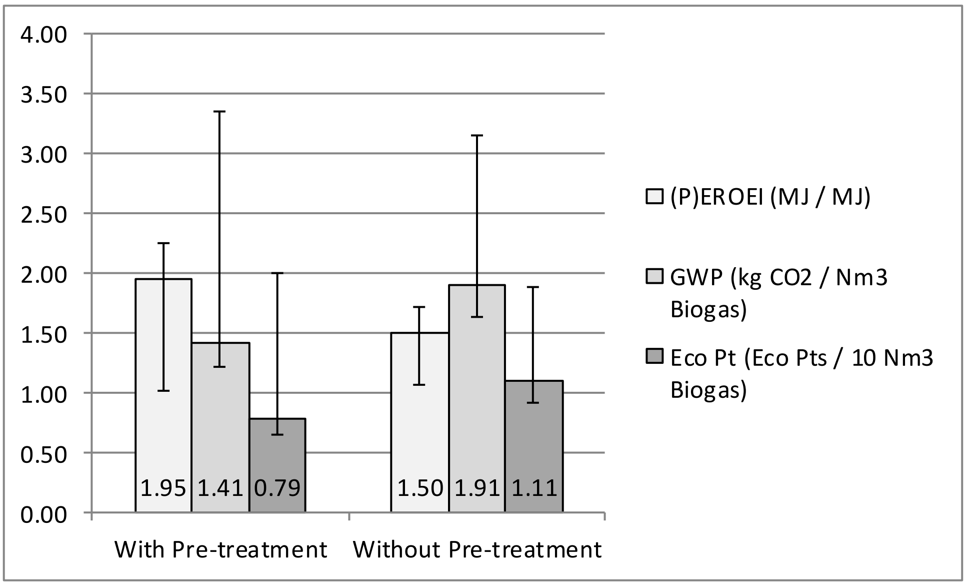
It has been shown that pre-treatment can significantly increase the biogas yield of grass and other sources of biomass (please refer to *Section 4.3.3 - Grass Pre-treatment*). The LST Department of Hanze University of Applied Science has provided information regarding biogas production from grass, using both pre-treatment and no pre-treatment, provided in *Appendix 11.4*. *Figure 5.2.1.1 - Biogas potential of common grass in laboratory experiments* shows the biogas potential of common grass, as well as the potential increase resulting from pre-treatment. However, it must be noted that in this study, pre-treatment consisted of microwaving the biomass and likely represents the absolute biogas potential of common grass, not a readily achievable potential. Still, the different potentials of pre-treated and non-treated grass are notable and support observations made in literature, such as (Uellendahl, et al., 2008).

Figure 5.2.1.1 - Biogas potential of common grass in laboratory experiments



In this study, it has been assumed that some method of pre-treatment (specifically ensiling followed by mulching) is always be used for grass feedstock. However, to justify this assumption, we must consider the impacts of pre-treatment. *Figure 5.2.1.2 - Relative impact of pre-treatment process* shows that on average, pre-treatment can improve the (P)EROI and reduce the GWP and environmental impact of the biogas production process. However, if pre-treatment requires too much energy input or does not significantly increase biogas potential, the net effect may be more detrimental than beneficial. The same holds for economic impacts: The pre-treatment process increases the cost of producing biogas, though this cost is (on average) offset by the greater amount of biogas produced.

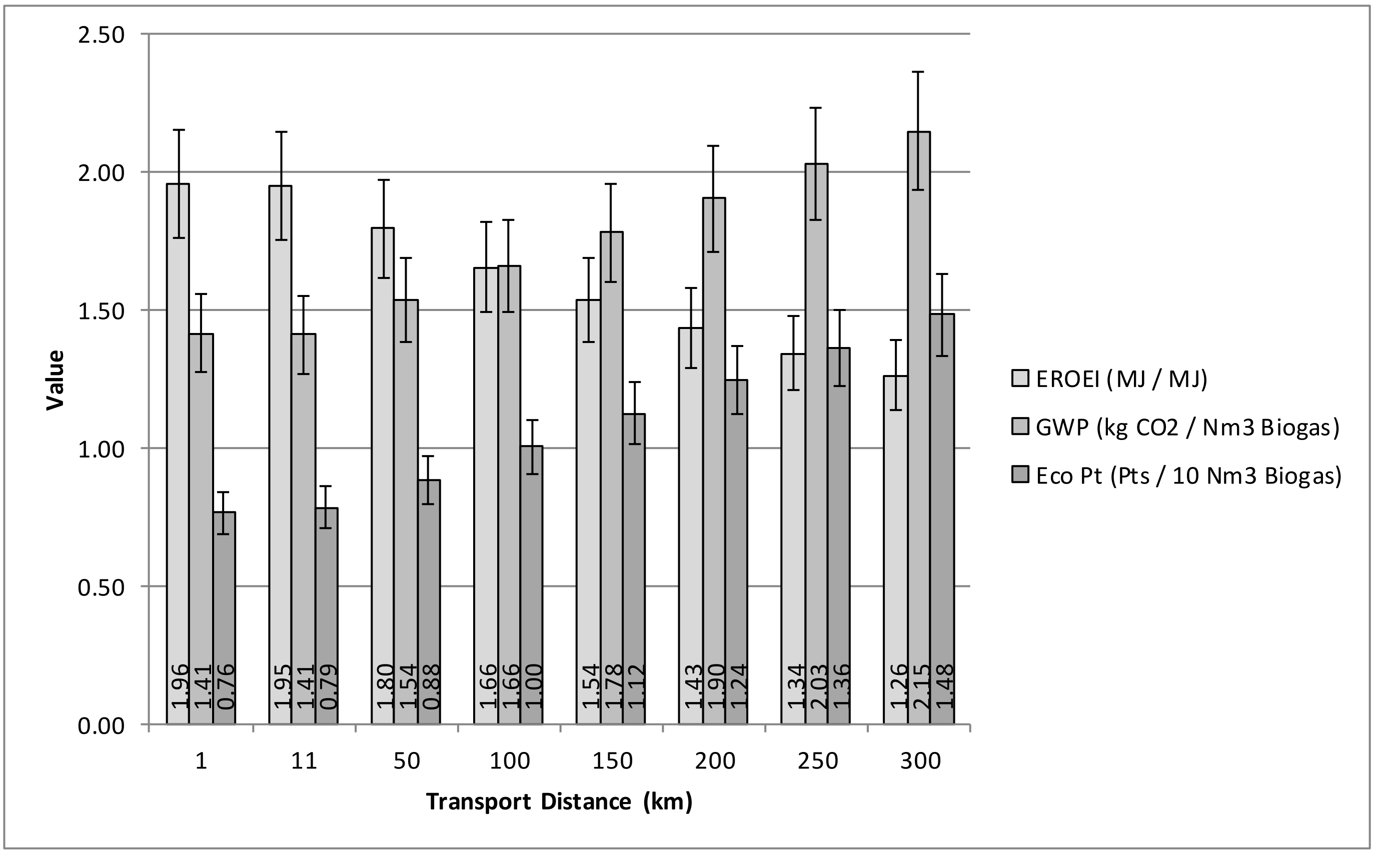
Figure 5.2.1.2 - Relative impact of pre-treatment process



5.4 Impacts of variations in transport distance of biomass

Due to the relatively high impact of the transportation process, transportation distance of biomass feedstock is a key variable when determining where to construct a biogas facility. *Figure 5.2.1.1 - Impact of varying transportation distance* shows how variations in transportation distance can affect the sustainability of a biogas production process. Predictably, (P)EROI decreases, while environmental impacts and GWP increase, as transportation distance increases. What is significant is the magnitude of the effect of changing transportation distance: increasing transportation distance from 11 to 100 km can lower net energy gains by nearly one third, while increasing GWP and environmental impact to a level comparable with natural gas production. At a transport distance of 300 km, the biogas production process has a low enough (P)EROI that it can no longer be considered a renewable energy source.

Figure 5.2.1.1 - Impact of varying transportation distance



6 Evaluation of the Biogas Production Model

In order to validate the data produced by the biogas production model, several steps were taken. First, the model was extensively analyzed to find any errors. The model also underwent a sensitivity analysis (described below) in order to ensure it was functioning in a predictable manner. Following this, the model was compared to case studies, such as (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011), to ensure results were comparable to those found in literature. The model was also compared to an economic model developed independently at the Hanze University of Applied Science by Jan Bekkering. This comparison showed a strong correlation between the results of the two models, within a range of 10%. Finally, the biogas production model was presented to other members of the FlexiGas project and submitted for their review.

6.1 Sensitivity Analysis of the Biogas Production Model

When performing an LCA, the quality of input data is of the utmost importance. Input data must be representative of a given scenario if the results are to convey an appropriate meaning. Therefore, it is important to compare and contrast different data sources, validate literature data with experimental results and clarify any assumptions which are made. In general, the range of data found within literature can be relatively high and these variations must still be represented within the final results and analysis.

Different scenarios have been calculated to determine the relative impact of variations in the primary variables. In this study, the input data which has the largest impact on the final results includes: Grass yields per hectare; Grass quality, i.e. the dry matter content and volatile organic dry matter content of the grass; Biogas potential, i.e. the expected biogas yield when digesting grass; Methane content of the biogas product. Other factors can also be varied, but their impacts are minimal.

For each input variable examined, the primary result is an average value obtained from comprehensive literature review and laboratory results. It is also the input data assumed for the Hoogkerk case study. The range presented in the results represents the extremes in biomass quantity and quality which have been observed in published studies. This range emphasizes the importance of determining local potentials for producing biogas, since slight changes in inputs can have profound impacts on the sustainability of a biogas production process.

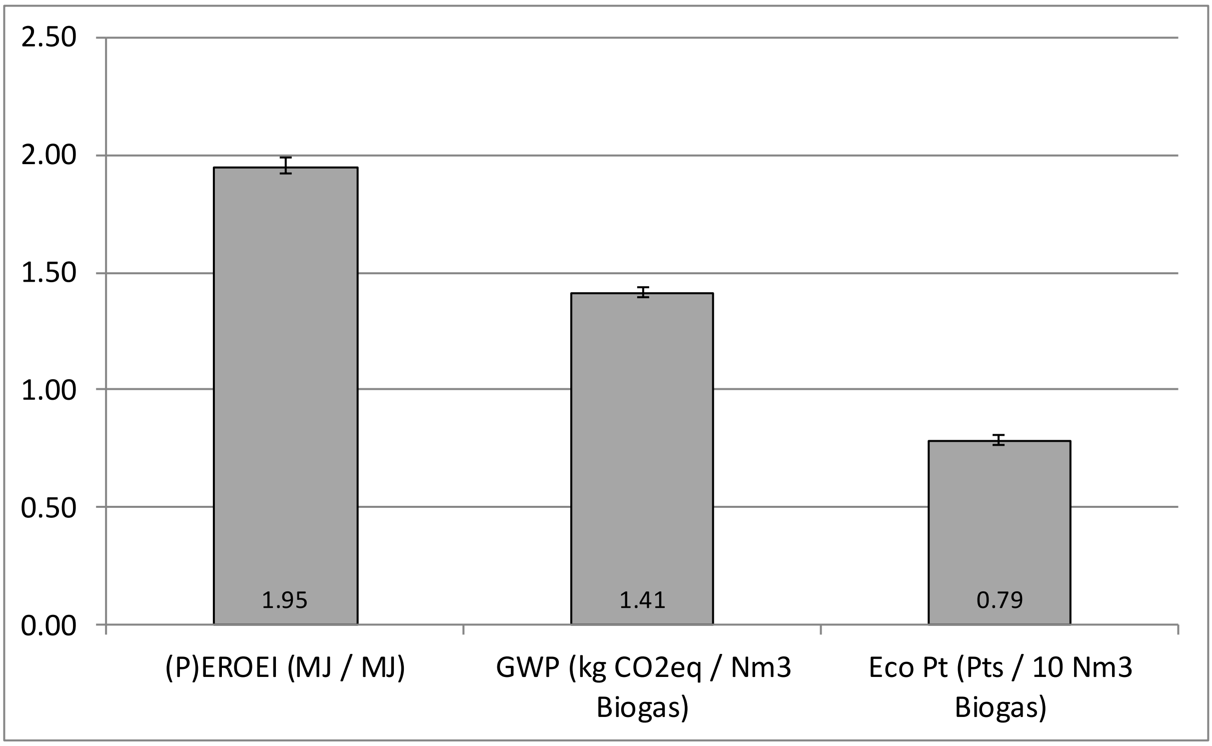
6.1.1 ... Impact of variations in grass yield

In this study, grass yields are measured in tons of dry matter per hectare. In literature, large variations in grass yields are reported, ranging from 2 – 15.5 $tons_{DM}$ ha^{-1} (Prochnow., et al., 2009). There are many factors which contribute to this large range of results and these must be defined in order to obtain a manageable range of numbers.

Agricultural practice plays a crucial role in biomass yields. Here, two techniques are defined: Intensive farming and landscape management. “Intensification […] seeks to increase the productivity on a given (or fixed) area of land by progressively increasing the inputs, including capital and labor” (Beranger). Some impacts of intensive farming (due to the use of chemical fertilizers, pesticides and herbicides) are noted in *Appendix 11.2.10*. Conversely, in landscape management, naturally-occurring plants are cut for safety or aesthetic reasons. Organic dry matter yields from landscape management areas are typically quite low since grass is only harvested 1-2 times per year, and generally after grass flowering, when organic dry matter content is at its lowest (Tuomisto, Hodge, Riordan, & Macdonald, 2012) (Morris, 2012). In this study, common grass is considered to be harvested by landscape management, while maize is considered to be farmed intensively.

Table 11.1.1.1 - Expected biomass yields for grass, in *Appendix 11.1.1*, displays reported grass yields for different cases. Notably, (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011) determined a grass yield of 3.96 – 6.12 $tons_{DM}$ ha^{-1} yr^{-1} from landscape management in a national park in north-east Germany. Because the harvesting conditions in this report closely match those assumed in this study, an average biomass yield of 5,000 kg_{DM} ha^{-1} yr^{-1}(±20%), or 14,286 kg_{FM} ha^{-1} (±20%), is assumed for grass. For comparison, maize silage is assumed to have an average annual production of 13,950 kg_{DM} ha^{-1} yr^{-1}(±10%), or 45,000 kg_{FM} ha^{-1} (±10%) (Bekkering, Broekhuis, & van Gemert, 2010). *Figure 6.1.1.1 - Sensitivity of variations in biomass yield on final results* shows the effects of variations in biomass yields by ±20%.

Figure 6.1.1.1 - Sensitivity of variations in biomass yield on final results

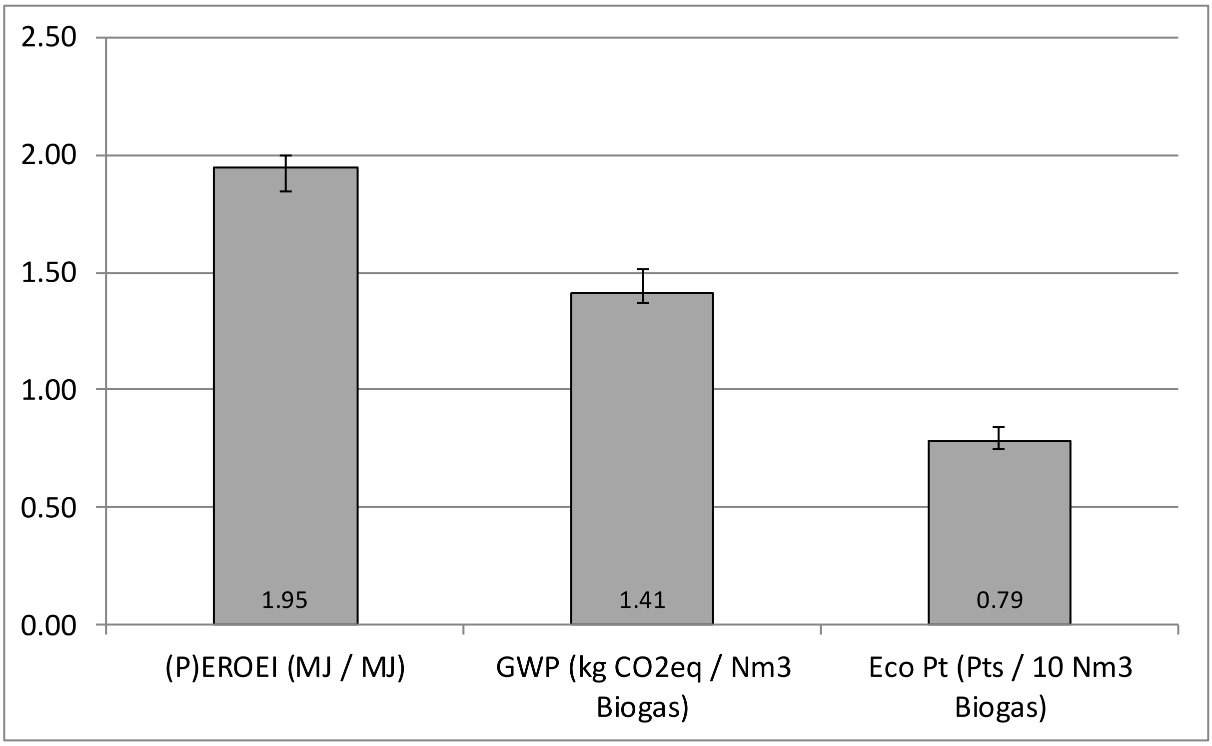


Grass species also has an impact on yields: some grass species grow faster than others and nutrient requirements can vary from species to species. Common grass within the Netherlands consists of several species of grass, notably perennial ryegrass, cocksfoot, tall fescue, red fescue, meadow fescue, meadow foxtail, timothy and reed canary grass (B.V. Euro Grass, 2009) (Prochnow., et al., 2009). However, it is notable that “the area-specific methane yield of grass species rather depends on the biomass yield than on the feedstock-specific methane yields” (Prochnow., et al., 2009). Climate and location will therefore play a large role in biomass yields. Climate and location define a plant’s growing season, water availability and soil quality. This study focuses on grass yields in the north-east Netherlands, a typical moderate coastal climate, with precipitation distributed relatively equally throughout the year (KNMI, 2011). However, due to the modular nature of the biogas production model, other growth scenarios for grass can easily be implemented and evaluated

6.1.2 ... Impact of variation in grass quality

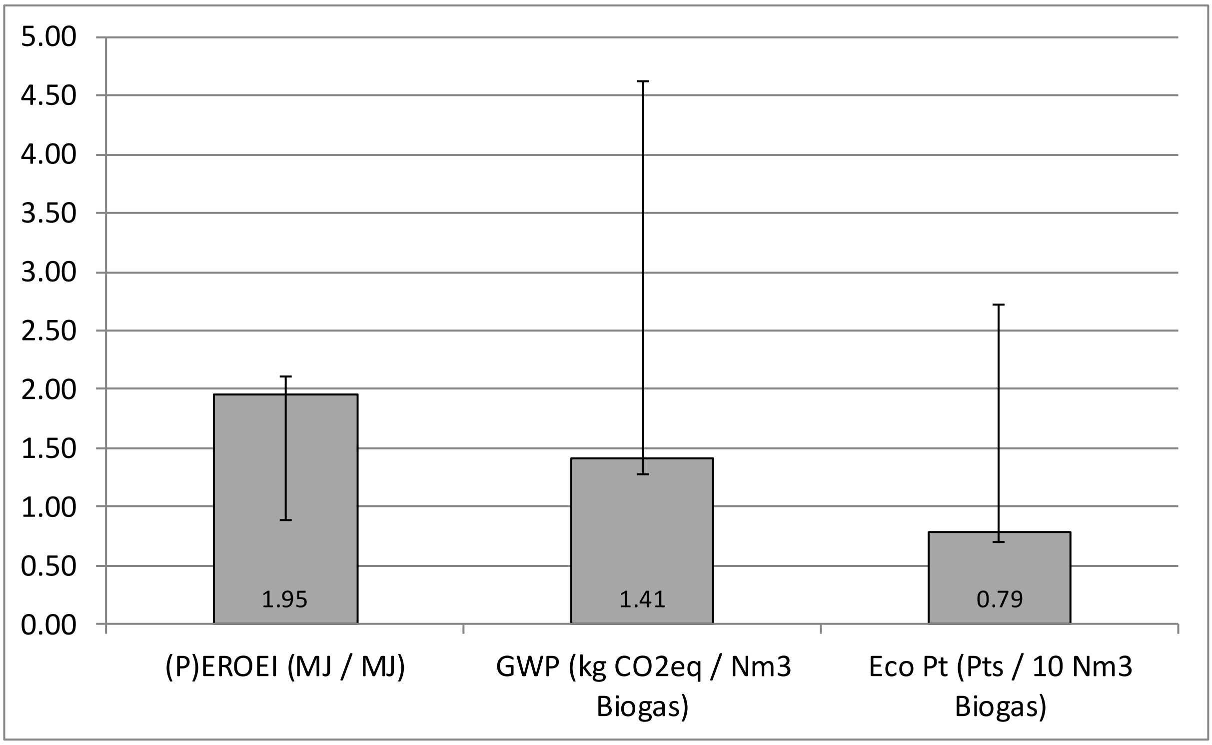
Grass has a highly variable makeup: the component makeup of grass depend on species, climate, soil quality and even time of year. Therefore, average values must be chosen to simulate the nutrient pathway through the model digestion process. It is particularly important to establish the average organic dry matter content of grass, since this directly influences the biogas yield of the anaerobic digestion process. In this study, the nutrient makeup of the grass feedstock is considered to be an average of several local grass species. *Table 11.1.2.1 - Nutrient concentrations of mixed grass species,* in *Appendix 11.1.2*, shows the primary nutrients present in various species of grass, as well as the average values used in the biogas production model. Organic dry matter is assumed to account for approximately 90% of the total amount of dry matter (Smyth, Murphy, & O'Brien, 2009). This is comparable with preliminary results presented by the Chamber of Agriculture of Lower Saxony (LWK Nds.) - German DELaND subproject, which estimate an organic dry matter content of 85 to 95 Wt% of total dry matter for landscape management grass. Surprisingly, variations in organic dry matter content (assuming a constant biomass yield) from 80% to 87.5% (on average) to 95% has a relatively low impact, as shown in *Figure 6.1.2.1 - Sensitivity of varying ODM from 80 to 95% on final results*.

Figure 6.1.2.1 - Sensitivity of varying ODM from 80 to 95% on final results



It is assumed that most grass contains 10 to 15% dry matter before harvest (Pré, 2008) (Smyth, Murphy, & O'Brien, 2009). However, the dry matter content can be increased to roughly 35% by allowing the grass to dry in the field for 6 to 24 hours, as is common practice (Fubbeker & Muller, 2003) (Gordon, Patterson, Porter, & Unsworth, 2000). *Figure 6.1.2.2 – Sensitivity of varying DM content from 10 to 45% on final results* shows the effect of dry matter content varying between 10 and 45%. In all cases, it is assumed that the total amount of organic dry matter remains constant. From this analysis, we can see that variations in dry matter content have a large effect on (P)EROI, GWP and environmental impact, since more (or possibly less) total mass has to be transported to produce the same amount of biogas as in the standard scenario of 35% DM content. Grass density is directly related to dry matter content: at 35% dry matter, grass has a density of roughly 550 kg m^{-3} (Tilvkiene, Vanslauskas, Navickas, Zuperka, Dabkevicius, & Kadziuliene, 2012) (KW, 2013).

Figure 6.1.2.2 – Sensitivity of varying DM content from 10 to 45% on final results

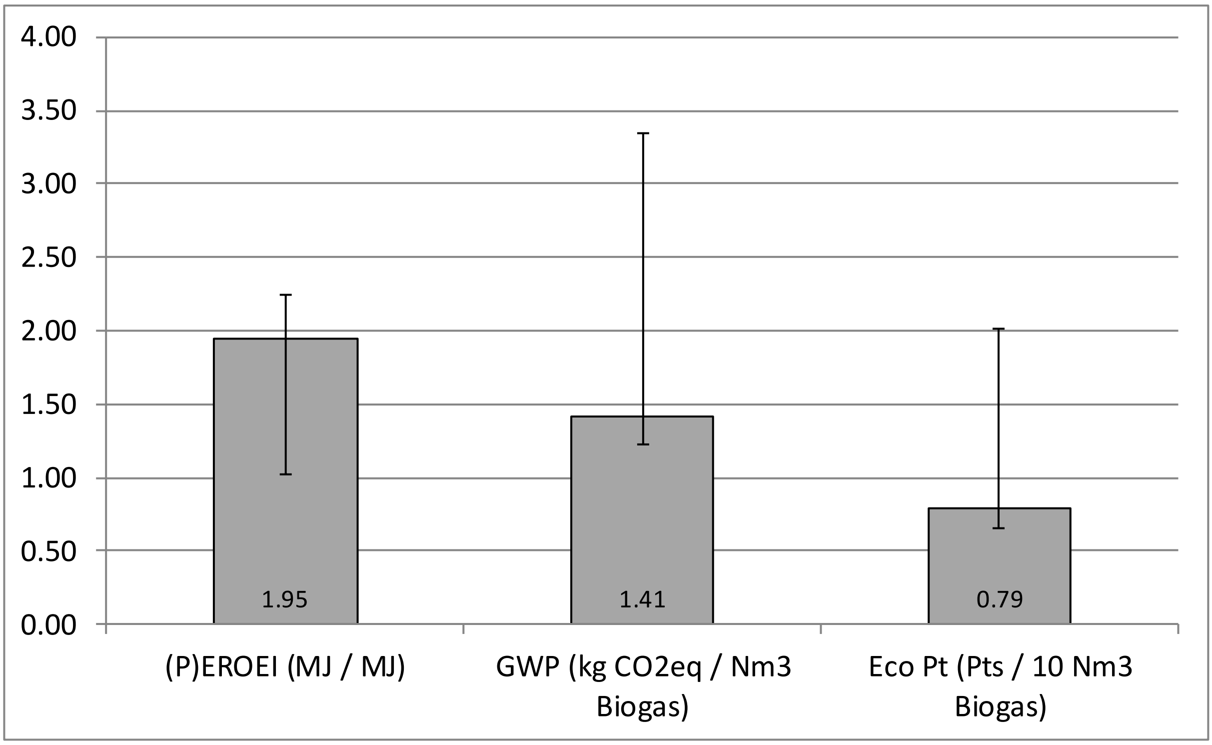


6.1.3 ... Impact of variations in biogas potential

The biogas potential is the amount of biogas which can be produced from one kilogram of volatile organic dry matter from a particular feedstock in anaerobic conditions. In this case, a conventional anaerobic digester with a retention time of 15 - 30 days is considered. From a case study performed by (Reumerman, 2013), using nature grass in the north-east Netherlands, it was determined that an average of 446 L of biogas will be produced per kilogram of organic dry matter of pre-treated and ensiled grass. These findings are supported by experiments performed by LST at Hanze University of Applied Science, which showed an ideal biogas potential for pre-treated common grass of approximately 510 L kg_{ODM}^{-1}. This result agrees with (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011), who report laboratory yields of 390 - 567 L kg_{ODM}^{-1} for common grass, which they estimate to be equivalent to 330 – 482 L kg_{ODM}^{-1} in practice. This is also comparable to preliminary results presented by the Chamber of Agriculture of Lower Saxony (LWK Nds.) - German DELaND subproject, which estimates a biogas yield for landscape management materials of 200 – 471 L kg_{ODM}^{-1}. As a reference, the biogas yields of maize are estimated to be approximately 600 L kg_{ODM}^{-1} (Hutnan, Spalkova, Kolesarova, & Lazor, 2010).

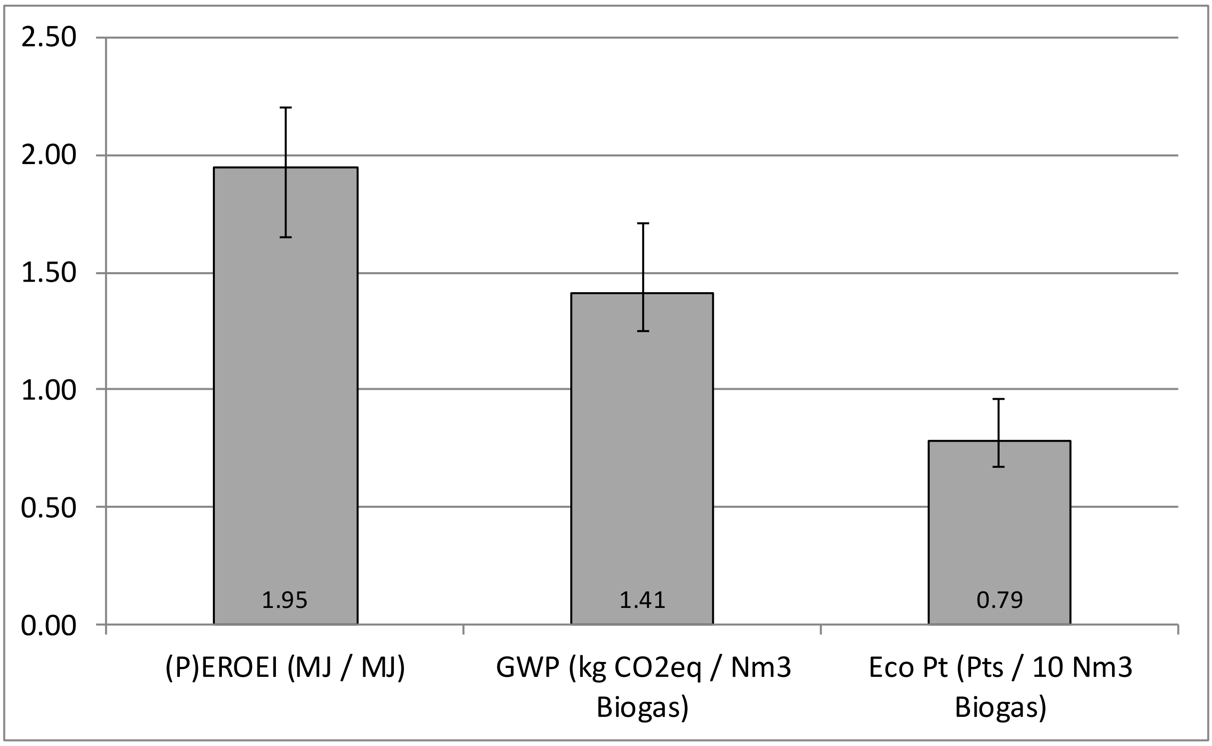
The biogas potential for common grass determined by (Reumerman, 2013), 446 L kg_{ODM}^{-1}, is assumed as the average biogas potential for common grass in this study. *Figure 6.1.3.1 - Sensitivity of variations in biogas potential on final results* details the dramatic impact variations in biogas potential can have on final results: It is apparent that environmental impacts and GWP of biogas production from grass can rise exceptionally high (and (P)EROI can drop precipitously low) if biogas yields are much lower than predicted. The sensitivity analysis shows the effect on final results as the biogas potential of grass is changed from a low estimate of 160 L kg_{ODM}^{-1} to 446 L kg_{ODM}^{-1} (on average) to 567 L kg_{ODM}^{-1}.

Figure 6.1.3.1 - Sensitivity of variations in biogas potential on final results



Biogas contains many different gasses: (Reumerman, 2013) determined that biogas produced from grass contains an average of 55 Vol% methane, giving grass a methane potential of 245 L kg_{ODM}^{-1}. This is confirmed by (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011), who found grass to have a methane potential of 215 – 312 L kg_{ODM}^{-1} in laboratory tests and 183 – 265 L kg_{ODM}^{-1} (equivalent to a 55% methane content of biogas) in practice. The Chamber of Agriculture of Lower Saxony (LWK Nds.) - German DELaND subproject, reports an average methane content of 50% for biogas produced from grass from landscape management. In this study, an average methane content of 55% was assumed for all biogas production. *Figure 6.1.3.2 - Sensitivity of variation of methane content in biogas on final* *results* demonstrates the effects of methane content of biogas varying from 45 Vol% to 55 Vol% (on average) to 65 Vol%.

Figure 6.1.3.2 - Sensitivity of variation of methane content in biogas on final results



The remainder of biogas is primarily composed of carbon dioxide, at 44 Vol% on average (AB Svenskt Gastekniskt Center, 2010). Other trace gasses and their relative amounts are described in *Table 11.1.3.1 – Average biogas* composition, in *Appendix 11.1.3*. Notably, ammonia and hydrogen sulfide are generally present, which are corrosive and toxic and must be removed from biogas before it can be distributed or combusted on-site.

6.2 Conclusions of the evaluation process

Based on the evaluation of the biogas production model, it has been concluded that the results of this study are presented with a degree of confidence of greater than 80% accuracy. There is room for error, as presented in the sensitivity analysis, though this error is largely systemic to biogas production from biomass. Therefore, this study concludes that the data presented is valid and useful; that the conclusions drawn are accurate and can be used as the basis for further research.

7 Discussion of LCA Results: Implications for the energy supply of Hoogkerk

This chapter focuses on the results of the LCA of the proposed production of biogas from common grass in the village of Hoogkerk, which are measured against alternate methods of gas production. The benefits and limitations of biogas production from grass are inferred from the results presented *Section 5 - Results* and discussed here in further detail.

7.1 Comparative LCA of biogas produced from common grass and alternate methods of energy production

Biogas production from grass compares favourably with other methods of gas production: the GWP and environmental impacts are relatively low and the (P)EROI is high enough to be considered sustainable. While biogas from grass is still not an ideal process (greenhouse gas emissions and environmental impacts still occur), it is an improvement over the current use of natural gas. Biogas from grass does not compare so well from an economic perspective, being the most expensive of the four scenarios examined. However, this high cost may be offset by government subsidies or lower feedstock costs associated with waste streams. Also, despite its high cost, biogas from grass remains the most environmentally sustainable of the gas production methods studied. It is therefore important to note which indicators are of the greatest importance for all stakeholders involved in an energy production process: From an environmental sustainability perspective, biogas from grass is likely a good alternative source of energy for the village of Hoogkerk. However, from an economic perspective, there are clearly better options.

7.1.1 ... (P)EROI of alternate energy production methods

Fossil fuels currently have a relatively high (P)EROI: (Hall & Klitgaard, 2012) reports an (P)EROI of 10-15:1 for natural gas, while (Pré, 2008) gives an estimate of 7.14:1. In any case, these ratios are significantly higher than those found for biogas production using the biogas production model. For example, biogas produced from grass has an average (P)EROI of 1.95:1 But while biogas cannot achieve the same energy returns as natural gas, it is important to note that the average (P)EROI of biogas production (for all scenarios examined in this study) is greater that 1.3:1, implying that biogas is a renewable resource.

As stated in *Section 2.1.3 - Process Energy Return On Investment*, it has been argued that humanity requires a minimum (P)EROI of 3:1 for energy production processes in order to maintain our modern lifestyle and infrastructure (Hall., Balogh, & Murphy, 2009). While biogas production cannot readily attain such high energy returns according to the results of this study, it must be noted that biogas is not humanity's sole source of renewable energy. Solar and wind energy have (P)EROIs of roughly 10:1 and 18:1, respectively (Hall & Klitgaard, 2012). If biogas is used in synergy with these other renewables, then a lower (P)EROI is likely acceptable and biogas can contribute towards future sustainable energy supplies.

7.1.2 ... GWP of alternate energy production methods

When considering GWP, natural gas has the largest impact on average of the scenarios examined. The GWP of biogas from all sources of biomass is comparable and on average shows a reduction when compared to natural gas. Since the carbon released from combusting plants can be recaptured when new plants are grown, emissions from biogas combustion can be "trapped" in a sustainable cycle. However, there are still indirect emissions from energy and material consumption during the biogas production process and global warming impacts are not avoided entirely. In this way, all three biogas production scenarios show the possibility for their GWP to be higher than that of natural gas. If care is not taken when designing a biogas production process, then the impact on global warming may be higher than that of the process which is intended to be offset. It is therefore important to design biogas production processes which operate in a sustainable way from a global warming point of view, where overall greenhouse gas emissions are definitively and significantly reduced.

7.1.3 ... Environmental impact of alternate energy production methods

When considering environmental impact, it is important to note the emphasis which Eco Indicator 99 places on land use: since intensive maize production requires many chemical inputs onto land, its environmental impact is considerably higher than the other processes to which it is compared. In addition, intensive maize production for producing biogas requires using land which could potentially be used for growing food crops – the 'Food vs. Fuel' debate is an important issue both socially and in terms of sustainably (Sexton, Rajagopal, Ziberman, & Hochman, 2008) (Thompson, 2012).

Also of note are the relatively low environmental impacts of biogas produced from common grass and organic waste. While these energy sources may appear less effective when considering other indicators, in terms of negative environmental effects, their relative impact is minimal. Grass in particular shows the lowest relative impact, due in no small part to the fact that no food-producing land is used and material and energy inputs are minimized in landscape management (i.e. non-intensive) practices.

7.1.4 ... Economic costs of alternate energy production methods

The cost of producing biogas from biomass is highly dependent on the cost of the feedstock, as shown in *Section 5.1.5 - Economic impact of various energy production*. It is notable that under the assumption of grass costing 36 € ton_{FM}^{-1}, biogas produced from grass has by far the highest cost of the scenarios studied. Although this cost may appear high, it does compare favourably with an economic model produced independently by Jan Bekkering at Hanze University of Applied Science. However, it was also shown that this cost could be reduced dramatically if the cost of the primary feedstock, common grass, is reduced. It is entirely plausible to receive income for receiving waste products, such as common grass. If we consider that a biogas facility receives 10 € ton^{-1} for grass (rather than spending 36 € ton^{-1}), the economic impact is enormously beneficial. Even a cost reduction to 20 € ton^{-1} can reduce the cost of biogas produced from grass to be competitive with biogas produced from maize. Clearly, the economic viability of a biogas production facility is highly dependent on the cost of its feedstock. In order for grass to be considered an economically viable alternative to maize or organic waste, the feedstock costs must likely be subsidized or an alternative low-cost source of grass must be exploited.

Biogas from maize is also relatively costly, but again, the cost of the feedstock is relatively high. In contrast, biogas produced from organic waste is the cheapest of the three biogas production scenarios, which is not surprising considering that the primary feedstock does not cost any money directly. Natural gas is the cheapest of the gas production methods, which is indicated by its high (P)EROI: high energy returns means that relatively little material and energy (and hence capital) must be invested in the production of natural gas.

For the village of Hoogkerk, feedstock cost may not be an issue, since much of the common grass in the area will be cut regardless and be regarded as a waste stream. It is entirely possible that much of the feedstock required for a biogas production process could be obtained for free or at a reduced rate. If such an arrangement exists, then biogas produced from grass becomes a financially competitive source of sustainable energy, one which bears further consideration.

7.1.5 ... Implications of model results for the village of Hoogkerk

The results discussed above are all in reference to a proposed energy scenario for the village of Hoogkerk. Producing biogas from common grass and cow manure from the local area can provide the village with roughly one half of its gas needs. As discussed, biogas produced from grass has many advantages, particularly in terms of reducing the carbon footprint and environmental impact of the village. Also, due to its (P)EROI of 1.92:1, biogas produced from grass can be considered a renewable source of energy.

But while biogas production from common grass is certainly feasible, it also has certain limitations. For instance, the large area of land which would be required to produce enough gas for one small village implies that biogas production from grass cannot be implemented everywhere. Also, the relatively high cost of producing biogas may prove prohibitive.

In summary, biogas production from common grass is a practical and implementable means of energy production which could help improve Hoogkerk's environmental sustainability. The high economic cost may be justified if environmental impact and GWP are a serious social concern. This study has demonstrated that it is plausible that a portion of Hoogkerk's gas needs could be substituted with gas produced from biogas: This would help reduce the environmental impacts of the village while improving the sustainability of Hoogkerk's energy supply.

7.2 Implications of grid injected gas compared to CHP utilization

As a further comparison, green gas can either be injected into the gas grid or combusted on-site in a CHP unit to produce electricity and heat. The advantage of the CHP scenario is that both the recovered heat and electricity produced can be used to power the biogas facility, thus reducing energy inputs and indirect impacts. In addition, biogas does not need to be upgraded before it is used, which again lowers the overall impact. However, running and maintaining a CHP unit is quite material and energy intensive, which increases the CHP scenario's overall environmental impact. In addition, once biogas is combusted in a CHP unit, the energy produced cannot be easily stored, which contradicts one of the primary motives for producing biogas: creating a storable and readily extractable form of renewable energy.

It is interesting to note the potential advantages of the CHP scenario: the results presented in *Section 5.2 - Impacts of grid injection of gas compared to CHP* show CHP use to be preferable in terms of GWP. However, it must be emphasized that the environmental sustainability of the CHP scenario depends largely on the amount of heat which can be recovered. As heat recovery decreases, the CHP scenario's impacts increase dramatically. Also, the gas grid injection scenario has the advantage of having a higher (P)EROI and lower cost per MWh, within the boundaries of this study.

The results of the scenario comparing grid-injected biogas and CHP production of heat and electricity have been normalized based on the energy content of the final product(s). However, the question arises as to whether or not we can directly compare the value of gas with that of heat and electricity - all energy is not necessarily equal. Because the normalizing factor is not necessarily equal in both cases, the results of this LCA cannot be directly compared. Therefore, these scenarios should be regarded independently: biogas utilization must be adapted for local requirements (i.e. CHP use if electricity generation is a priority, gas grid injection if distributable biogas is a priority).

For the village of Hoogkerk, the end use of biogas depends largely on local energy requirements. Heat recovered from CHP use may be used for district heating, reducing the consumption of natural gas. Additionally, since the Dutch electricity mix is relatively dirty (Pré, SimaPro Ecoinvent Database, 2013), green electricity production may be a more effective means of off-setting the village's environmental impacts. Biogas can play an important role in assisting the integration of solar and wind electricity production: Biogas can be combusted to produce electricity during times when solar and wind electricity generation plants are not producing. However, this strategy presumes an intermittent use of CHP production and that biogas is still stored in the grid during times when it is not required for electricity generation. Also, gas has a very different application from electricity and cannot currently be easily substituted by other sources of renewable energy (unlike electricity production).. This implies that regardless of the benefits of utilizing a CHP unit, biogas has unique qualities which may make grid injection a preferable option regardless of impacts.

7.3 Implications of the pre-treatment process

As discussed in *Section 5.3 - Impacts of the* pre-treatment, pre-treatment has the potential to increase biogas yields by as much as 1.5 times. However, it must be noted that pre-treatment also requires additional energy and material input into the biogas production process. While it is possible that pre-treatment will significantly increase the (P)EROI of the biogas production process, it must be noted that there is also the potential to have a lower (P)EROI if the pre-treatment process does not effectively increase biogas yields. Roughly speaking, a pre-treatment process should increase biogas yields by a minimum of 25 $Nm^3\ kg_{FM}^{-1}$ if it is to have a net benefit for energy production.

For GWP and environmental impact, the reverse is true: If biogas yields are not significantly increased by the pre-treatment process, then GWP and Eco Points will increase, resulting in a relatively greater environmental impact. It is therefore important to ensure that any pre-treatment process is actually contributing to increased energy returns before investing in such a process. The pre-treatment process must increase biogas yields enough that the net energy returns increase if it is to contribute towards a sustainable process.

For the village of Hoogkerk, it is likely quite beneficial to implement a pre-treatment process for grass: The potential increase in biogas potential of grass by pre-treatment has been clearly demonstrated (please refer to *Section 5.3*). The advantages of pre-treatment very likely outweigh the increased investment, to the point of making pre-treatment a near essential step in any biogas production process involving grass as a feedstock.

7.4 Implications of the evaluation of transportation distance of biomass

When designing a biogas facility, location is important. *Section 5.4 - Impacts of variations in transport distance* describes the relatively large impact of increasing average transportation distance of grass by a mere 100 km. In a global market, it may prove financially beneficial to import biomass feedstock from hundreds of kilometers away. However, from a sustainability point of view, this would prove disastrous.

It is perhaps obvious, but it bears stating nonetheless: Biomass which is used to produce biogas should be transported as little as possible. In order to maximize environmental sustainability, biogas facilities should be constructed as close to the source of their biomass inputs as reasonably possible and only local resources should be exploited. It is therefore beneficial for villages such as Hoogkerk to operate decentralized, small-scale biogas plants which minimize transportation distances and contribute towards local energy requirements.

8 Conclusions

The primary question of this study was to determine whether or not common grass is an effective alternative means of sustainable energy production. The case study examining the village of Hoogkerk highlights the potential benefits and limitations of such a scheme. This case study demonstrates that biogas production from grass can be considered a renewable resource, so long as (P)EROI remains above a ratio of 1.3:1. Additionally, biogas produced from grass is a good option for reducing greenhouse gas emissions (slightly) and environmental impacts (significantly), when compared to the present production of natural gas. Further, the biogas production process has the advantage of offsetting natural gas use and utilizing two waste streams: common grass and cow manure. Biogas production from common grass can also make use of a sustainable nutrient cycle, since digestate can be utilized as an organic fertilizer. While biogas production from common grass may not always be a superior source of energy due to its relatively low (P)EROI and high economic cost, it is clearly advantageous as a flexible and storable form of renewable energy which is also environmentally sustainable.

It is important to note that the (P)EROI for **all** biogas production options examined remains at a ratio of less than 3:1. While these are still viable renewable processes (the (P)EROI is typically greater than 1.3:1), without proper analysis, a biogas production facility could easily consume more energy than it produces. The importance of a comprehensive LCA for any biogas production process is emphasized: It is essential to analyze each individual biogas production scenario in order to ensure that biogas can be produced and utilized in a sustainable manner. Further, the global warming potential of biogas production is not significantly smaller than the direct use of fossil fuels. This leads one to conclude that while biogas from grass may be viewed as having a relatively low GWP, greenhouse gas emissions are still released and this process is not a perfect alternative to natural gas production. Finally, the environmental impact of biogas production from any source of biomass is on average lower, but potentially even higher than the direct use of fossil fuels. This leads to the question of whether or not biogas production is a technology which should be invested in to reduce environmental impacts, to which the simple answer is "maybe". What should be clear from this study is that biogas is a versatile and effective renewable energy technology, but whether it helps reduce global warming effects and environmental impacts is very situation and practice dependent. In conclusion, biogas production from common grass is not a concept without limitations, but it does have the potential to play a role in sustainable energy production. It is, however, important to apply that role only when and where it is appropriate: Any biogas production process must be employed in a limited and responsible manner and must be seriously analyzed and optimized to reduce impacts and contribute in a meaningful way to a sustainable future.

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10 Index

11 Appendices

The appendices contain all of the information relevant to the LCA of biogas production from common grass. Also included is information relevant to the construction and operation of the biogas production model.

11.1 Primary Database

The primary database includes all the information relevant to the primary inputs in the biogas production model.

11.1.1.. Grass Yields

Table 11.1.1.1 - Expected biomass yields for grass

Farming Technique	Expected Yield ($tons_{DM}$ ha^{-1} yr^{-1})
Extensive farming on Austrian hillside, 1-3 cuts per year (Prochnow., et al., 2009)	4.2 – 6.5
Bavarian forestland, 3 cuts per year, no fertiliser used (Prochnow., et al., 2009)	4.2 – 5.2
Perennial grass grown on light soil with humus content <2% in Lithuania (Jasinskas, Zaltauskas, & Kryzeviciene, 2008)	6.3 – 8.8 (2.8 – 6.5 in unfavorable conditions)
Extensive grass farming, 2 cuts per year, Belgium (Gerin, Vliegen, & Jossart, 2008)	5 (+/- 10%)
Grass from landscape management (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011)	3.96 – 6.12
Extensive organic production of grass on a natural meadow, 1 cut per year, 10-15% Dry Matter, Switzerland (Jungbluth, et al., 2007)	3 (± 10%)

11.1.2.. Grass Nutrient Content

Table 11.1.2.1 - Nutrient concentrations of mixed grass species

Nutrient	Meadow Foxtail and reed canary grass in Germany (g kg_{DM}^{-1}) (Prochnow, Heiermann, Plochl, Amon, & Hobbs, 2009)	Five semi-natural grassland communities in Germany (g kg_{DM}^{-1}) (McEniry & O'Kiely, 2013)	Assumed Average Values (g kg_{DM}^{-1})
Nitrogen	7.4 – 18.1	9.0 – 18.9	13.3
Phosphate	2.5 – 8.9	n.r.	5.7
Potassium	2.1 – 17.8	3 – 15	9.5
Magnesium	0.81 – 2.7	n.r.	1.8
Sodium	0.43 – 2.8	n.r.	1.6

11.1.3.. Biogas Composition

Table 11.1.3.1 – Average biogas composition (AB Svenskt Gastekniskt Center, 2010) (Rasi, Veijanen, & Rintala, 2007) (Rasi S. , 2009)

Gas	Volume Percent (%)	
	Average	**Range**
Methane (CH_4)	55	35 – 65
Carbon Dioxide (CO_2)	44	34 - 64
Nitrogen (N_2)	0.2	<1 - 2
Oxygen (O_2)	0.1	<0.1 - 1
	Concentration (ppm)	
Ammonia (NH_3)	1.5	0.5 - 100
Hydrogen Sulfide (H_2S)	500	0 – 4,000

11.1.4.. Primary Inputs

Table 11.1.4.1 - Variable primary inputs

Variable	Average	Range	Unit
Grass from landscape management (Reumerman, 2013) (Gerin, Vliegen, & Jossart, 2008) (Smyth, Murphy, & O'Brien, 2009)			
Biomass Yield	5	2.0 – 7.75	$tons_{DM}$ / ha yr
Dry Matter Content	35	15 – 45	Mass %
Biogas Potential	0.446	0.35 – 0.57	Nm^3 / kg_{FM}
Methane Content of Biogas	55	45 – 65	Vol %
Maize from intensive farming (Hutnan, Spalkova, Kolesarova, & Lazor, 2010) (Wageningen UR Livestock Research, 2013) (Lems, 2012)			
Biomass Yield	14	7.5– 22	$tons_{DM}$ / ha yr
Dry Matter Content	31	19 – 45	Mass %
Biogas Potential	0.60	0.50 – 0.70	Nm^3 / kg_{FM}
Methane Content of Biogas	55	50 – 65	Vol %
Municipal Organic Household Waste (StatWeb) (AB Svenskt Gastekniskt Center, 2010)			
Biomass Yield	4,750	4,250 - 5,200	$tons_{DM}$ / yr
Dry Matter Content	50	30 – 60	Mass %
Biogas Potential	0.26	0.15 – 0.35	Nm^3 / kg_{FM}
Methane Content of Biogas	55	45 - 65	Vol %
Natural Gas			
It is assumed that data from SimaPro regarding natural gas has a margin of error of 10%.			

11.2 Impact Coefficient Database

The impact coefficient database contains important information regarding the impacts of materials and energy inputs in the biogas production process.

11.2.1.. Agricultural Practices

Table 11.2.1.1 – Impacts of agricultural practices (Pré, SimaPro Ecoinvent Database, 2013)

Agricultural Practice	Energy Invested	Units
Mowing	384	MJ / ha
Tedding	181	MJ / ha
Swathing	271	MJ / ha
Collection and Loading for Transport	10.5	MJ / m^3
Agricultural Practice	**Global Warming Potential**	**Units**
Mowing	23.3	kgCO_2eq / ha
Tedding	10.8	kgCO_2eq / ha
Swathing	16.2	kgCO_2eq / ha
Collection and Loading for Transport	0.62	kgCO_2eq / m^3
Agricultural Practice	**Ecological Impact**	**Units**
Mowing	2.92	Eco Points / ha
Tedding	1.36	Eco Points / ha
Swathing	2.02	Eco Points / ha
Collection and Loading for Transport	0.0788	Eco Points / m^3

11.2.2.. Transport

Table 11.2.2.1 - Impacts of truck transport (Pré, SimaPro Ecoinvent Database, 2013) (Bekkering, Broekhuis, & van Gemert, 2010)

Impact Category	Impact	Units
Energy Invested, loaded haul	2.36	MJ / ton.km
Global Warming Potential, loaded haul	0.137	kgCO_2eq / ton.km
Environmental Impact, loaded haul	0.0136	Eco Points / ton.km
Energy Invested, empty haul	0.432	MJ / ton.km
Global Warming Potential, empty haul	0.0297	kgCO_2eq / ton km
Environmental Impact, empty haul	0.0027	Eco Points / ton.km
Diesel Fuel Costs	0.0496	€ ton^{-1} km^{-1}

Table 11.2.2.2 – Impacts of front-end loader use (Pré, SimaPro Ecoinvent Database, 2013)

Impact Category	Impact	Units
Energy Invested	5.28	MJ / ton.km
Global Warming Potential	.309	kgCO_2eq / ton.km
Environmental Impact	.0379	Eco Points / ton.km

11.2.3.. Pre-treatment and Digestion

Table 11.2.3.1 - Impacts of grass pre-treatment (Pré, SimaPro Ecoinvent Database, 2013)

Impact Category	Value	Unit
Energy Invested	2.05	MJ / ton
Global Warming Potential	0.190	kgCO_2eq / ton
Environmental Impact	0.0113	Eco Points / ton

Table 11.2.3.2 - Energy requirements for digestion process (Borjesson, 2006)

Impact Category	Value	Unit
Energy use of digester for manure per kg		
Electricity use	0.026	MJ/kg
Heat use	0.190	MJ/kg
Energy use of digester for maize per kg		
Electricity use	0.092	MJ/kg
Heat use	0.540	MJ/kg
Energy use of digester for grass per kg		
Electricity use	0.079	MJ/kg
Heat use	0.450	MJ/kg
Energy use of digester for municipal waste per kg		
Electricity use	0.115	MJ/kg
Heat use	0.160	MJ/kg

11.2.4.. Biogas Upgrading and Grid Injection

Table 11.2.4.1 - Energy requirements for carbon scrubbing (Lehtomaki, 2007)

Impact Category	Value	Unit
Electricity use	0.8280	MJ/Nm3

Table 11.2.4.2 - Energy use for gas grid injection (Weidenaar, 2013)

Impact Category	Value	Unit
Electricity use	0.0002	MJ/Nm3

11.2.5.. CHP Unit Impacts

Table 11.2.5.1 - Impact of CHP exhaust gases (Pré, SimaPro Ecoinvent Database, 2013) (Kristensen, 2005)

Impact Category	Value	Unit
Indirect CO2eq	8.07	kgCO2eq/Nm3
Indirect EcoPoints	2.01	Pt/Nm3

11.2.6.. Digestate Treatment and Utilization

Table 11.2.6.1 - Energy use for digestate separation - (VITO, 2012)

Impact Category	Value	Unit
Electricity use	0.0047	MJ/kg

Table 11.2.6.2 - Impacts of digestate off-site disposal (Wageningen UR Livestock Research, 2013)

Impact Category	Value	Unit
Costs	8.00	€/m3
Indirect Energy	1.56	MJ/m3
Indirect CO2eq	0.148	kgCO2eq/m3
Indirect EcoPoints	0.0163	Pt/m3

11.2.7.. Maize Production

Table 11.2.7.1 - Impacts of maize silage production (Pré, SimaPro Ecoinvent Database, 2013) (Wageningen UR Livestock Research, 2013)

Impact Category	Value	Unit
Costs	0.035	€/kg
Indirect Energy	0.40	MJ/kg
Indirect CO2eq	0.05	kgCO2eq/kg
Indirect EcoPoints	0.02	Pt/kg

11.2.8.. Municipal Organic Household Waste

Table 11.2.8.1 - Impacts of collecting municipal organic household waste (Pré, SimaPro Ecoinvent Database, 2013) (Bekkering, Broekhuis, & van Gemert, 2010)

Impact Category	Value	Unit
Costs	0.0496	€/ton.km
Indirect Energy	19.400	MJ/ ton.km
Indirect CO2eq	1.310	kgCO2eq/ ton.km
Indirect EcoPoints	0.116	Pt/ ton.km

11.2.9.. Natural Gas Production

Table 11.2.9.1 - Impacts of natural gas production (Pré, SimaPro Ecoinvent Database, 2013) (Wikipedia) (Energieprijzen, 2014)

Impact Category	Value	Unit
Costs	0.63	€/Nm3
Direct Energy	35.09	MJ/Nm3
Direct CO2eq	1.80	kgCO2eq/Nm3
Direct EcoPoints	0.00	Pt/Nm3
Indirect Energy	4.91	MJ/Nm3
Indirect CO2eq	0.11	kgCO2eq/Nm3
Indirect EcoPoints	0.12	Pt/Nm3

11.2.10 Chemical Inputs

Table 11.2.10.1 - Impact of chemical fertilizers (Pré, SimaPro Ecoinvent Database, 2013) (Wageningen UR Livestock Research, 2013)

Impact Category	Value	Unit
Nitrogen fertilizer		
Costs	1.10	€/kg
Indirect Energy	58.94	MJ/kg
Indirect CO2eq	8.55	kgCO2eq/kg
Indirect EcoPoints	0.42	Pt/kg
Phosphors fertilizer		
Costs	1.05	€/kg
Indirect Energy	49.30	MJ/kg
Indirect CO2eq	2.62	kgCO2eq/kg
Indirect EcoPoints	0.41	Pt/kg
Potassium fertilizer		
Costs	0.65	€/kg
Indirect Energy	24.40	MJ/kg
Indirect CO2eq	1.44	kgCO2eq/kg
Indirect EcoPoints	0.19	Pt/kg

Table 11.2.10.2 - Impact of chemical pesticides (Pré, SimaPro Ecoinvent Database, 2013) (Wageningen UR Livestock Research, 2013)

Impact Category	Value	Unit
Costs	7.5	€/kg
Indirect Energy	154.00	MJ/kg
Indirect CO2eq	9.37	kgCO2eq/kg
Indirect EcoPoints	0.91	Pt/kg

11.2.11 Energy Carriers

Table 11.2.11.1 - Impact of electricity from the Dutch international grid (Pré, SimaPro Ecoinvent Database, 2013) (Energieprijzen, 2014)

Impact Category	Value	Unit
Costs	0.06	€/MJ
Direct Energy	1.0000	MJPE / MJ
Indirect Energy	2.0500	MJ/MJ
Indirect CO2eq	0.1900	kgCO2eq/MJ
Indirect EcoPoints	0.0113	Pt/MJ

Table 11.2.11.2 - Impact of heat provided by the combustion of natural gas (Pré, SimaPro Ecoinvent Database, 2013) (Energieprijzen, 2014)

Impact Category	Value	Unit
Costs	22.05	€/MJ
Direct Energy	1.0000	MJ/MJ
Indirect Energy	1.2000	MJ/MJ
Indirect CO2eq	0.0683	kgCO2eq/MJ
Indirect EcoPoints	0.0041	Pt/MJ

Table 11.2.11.3 - Impact of diesel fuel (Pré, SimaPro Ecoinvent Database, 2013) (Centraal Bureau voor de Statistiek, 2014)

Impact Category	Value	Unit
Costs	1.46	€/kg
Direct Energy	43.10	MJ/kg
Direct CO2eq	3.282	kgCO2eq/kg
Direct EcoPoints	0.0397	Pt/kg
Indirect Energy	12.00	MJ/kg
Indirect CO2eq	0.60	kgCO2eq/kg
Indirect EcoPoints	0.18	Pt/kg

11.2.12 Gas Properties

Table 11.2.12.1 - Properties of natural gas (Wikipedia)

Impact Category	Value	Unit
Energy Content	35	MJ / Nm^3
Density	0.83	kg / Nm^3

Table 11.2.12.2 - Properties of methane (Wikipedia)

Impact Category	Value	Unit
Energy Content	39	MJ / Nm^3
Density	0.72	kg / Nm^3

Table 11.2.12.3 - Impact of methane leakage (Pré, SimaPro Ecoinvent Database, 2013)

Impact Category	Value	Unit
Indirect CO2eq	24.00	kgCO2eq/Nm3
Indirect EcoPoints	0.15	Pt/Nm3

Table 11.2.12.4 - Impact of nitrous oxide leakage (Pré, SimaPro Ecoinvent Database, 2013)

Impact Category	Value	Unit
Indirect CO2eq	24.00	kgCO2eq/Nm3
Indirect EcoPoints	0.15	Pt/Nm3

11.3 Embodied Energy Database

The embodied energy database summarizes the impacts of the construction of all significant facilities and equipment.

11.3.1.. Farm Equipment

Table 11.3.1.1 - Embodied energy of farming equipment (Pré, SimaPro Ecoinvent Database, 2013)

Impact Category	Value	Unit
Costs	2.00	€/kg
Direct Energy	74.90	MJ/kg
Direct CO2eq	3.81	kgCO2eq/kg
Direct EcoPoints	0.48	Pt/kg

11.3.2.. Storage Facilities

Table 11.3.2.1 - Embodied energy of storage facilities (Pré, SimaPro Ecoinvent Database, 2013) (Wageningen UR Livestock Research, 2013)

Impact Category	Value	Unit
Embodied energy manure storage tank per m3		
Costs	40	€/m3
Direct Energy	338.89	MJ/m3
Direct CO2eq	78.78	kgCO2eq/m3
Direct EcoPoints	4.50	Pt/m3
Embodied energy digestate storage tank per m3		
Costs	40	€/m3
Direct Energy	178.73	MJ/m3
Direct CO2eq	45.82	kgCO2eq/m3
Direct EcoPoints	2.42	Pt/m3
Embodied energy trench silo per m3		
Costs	40	€/m3
Direct Energy	398.19	MJ/m3
Direct CO2eq	283.56	kgCO2eq/m3
Direct EcoPoints	15.54	Pt/m3

11.3.3.. Digester

Table 11.3.3.1 - Embodied energy of digester (Pré, SimaPro Ecoinvent Database, 2013) (Bekkering, Broekhuis, & van Gemert, 2010) (Wageningen UR Livestock Research, 2013)

Impact Category	Value	Unit
Embodied energy digester tanks per ton/yr input (biomass)		
Costs	412.5	€/(ton/yr)
Direct Energy	132.50	MJ/(ton/yr)
Direct CO2eq	21.63	kgCO2eq/(ton/yr)
Direct EcoPoints	1.40	Pt/(ton/yr)
Embodied energy digester tanks per produced Nm3/hr (biogas)		
Costs	4,500	€/(Nm3/hr)
Direct Energy	4240	MJ/(Nm3/hr)
Direct CO2eq	692	kgCO2eq/(Nm3/hr)
Direct EcoPoints	44.80	Pt/(Nm3/hr)
Embodied energy per m2 of infra around digester		
Costs	32	€/m2
Direct Energy	173.79	MJ/m2
Direct CO2eq	40.40	kgCO2eq/m2
Direct EcoPoints	2.31	Pt/m2

11.3.4.. Biogas Cleaning and Upgrading Equipment

Table 11.3.4.1 - Embodied energy of biogas upgrading equipment (Pré, SimaPro Ecoinvent Database, 2013) (Bekkering, Broekhuis, & van Gemert, 2010)

Impact Category	Value	Unit
Costs	0.087	€/Nm3
Direct Energy	9275	MJ/Nm3
Direct CO2eq	537.50	kgCO2eq/Nm3
Direct EcoPoints	156	Pt/Nm3

11.3.5.. Combined Heat and Power Unit

Table 11.3.5.1 - Embodied energy of 500 kWe CHP unit (Pré, SimaPro Ecoinvent Database, 2013) (Blokhina, Prochnow, Plochl, Luckhaus, & Heiermann, 2011)

Impact Category	Value	Unit
Costs	2,943,632	€
Direct Energy	1,300,000	MJ
Direct CO2eq	76,200	kgCO2eq
Direct EcoPoints	6,000	Pt

11.4 Results

Presented here are the experimental results of common grass co-digestion with cow manure (with and without pre-treatment), as provided by the LST Department of Hanze University of Applied Sciences. Control batches of cow manure only were also measured and subtracted from the final results of grass / manure co-digestion in order to obtain the biogas potential of common grass only. These results are presented below. For both pre-treatment and non-treatment scenarios, grass was mulched in a blender. The pre-treatment scenario underwent the additional process of microwaving the grass feedstock.

Figure 11.3.5.1 - Biogas yields from common grass (no pre-treatment)

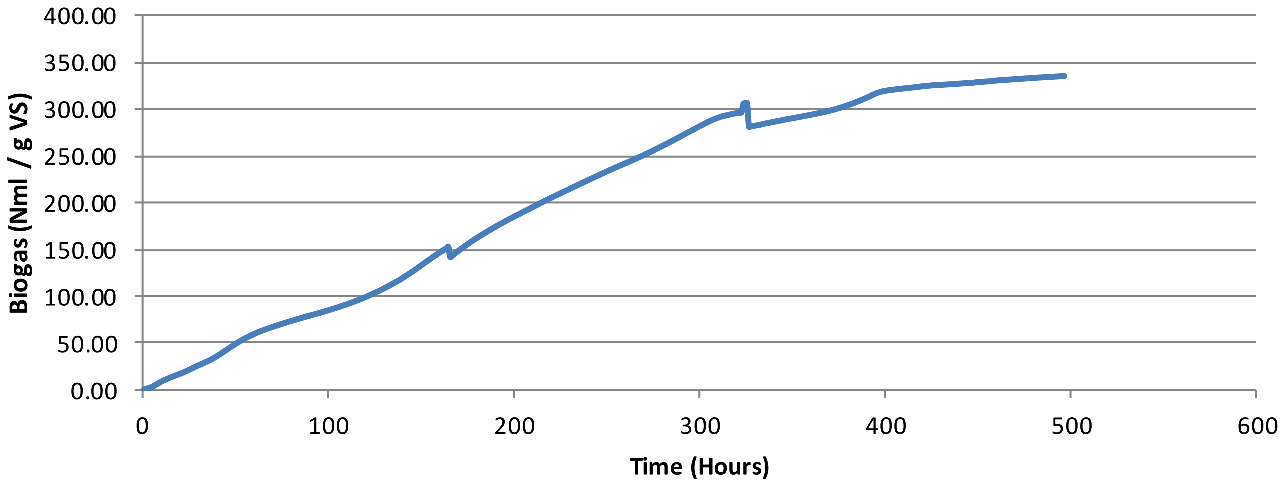
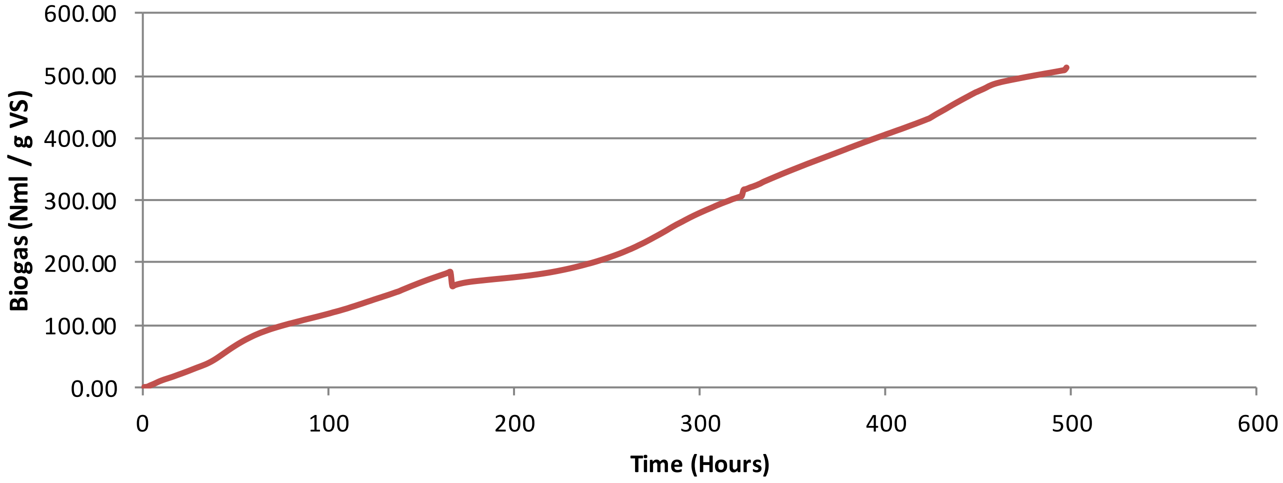


Figure 11.3.5.2 - Biogas yields from common grass (with pre-treatment)



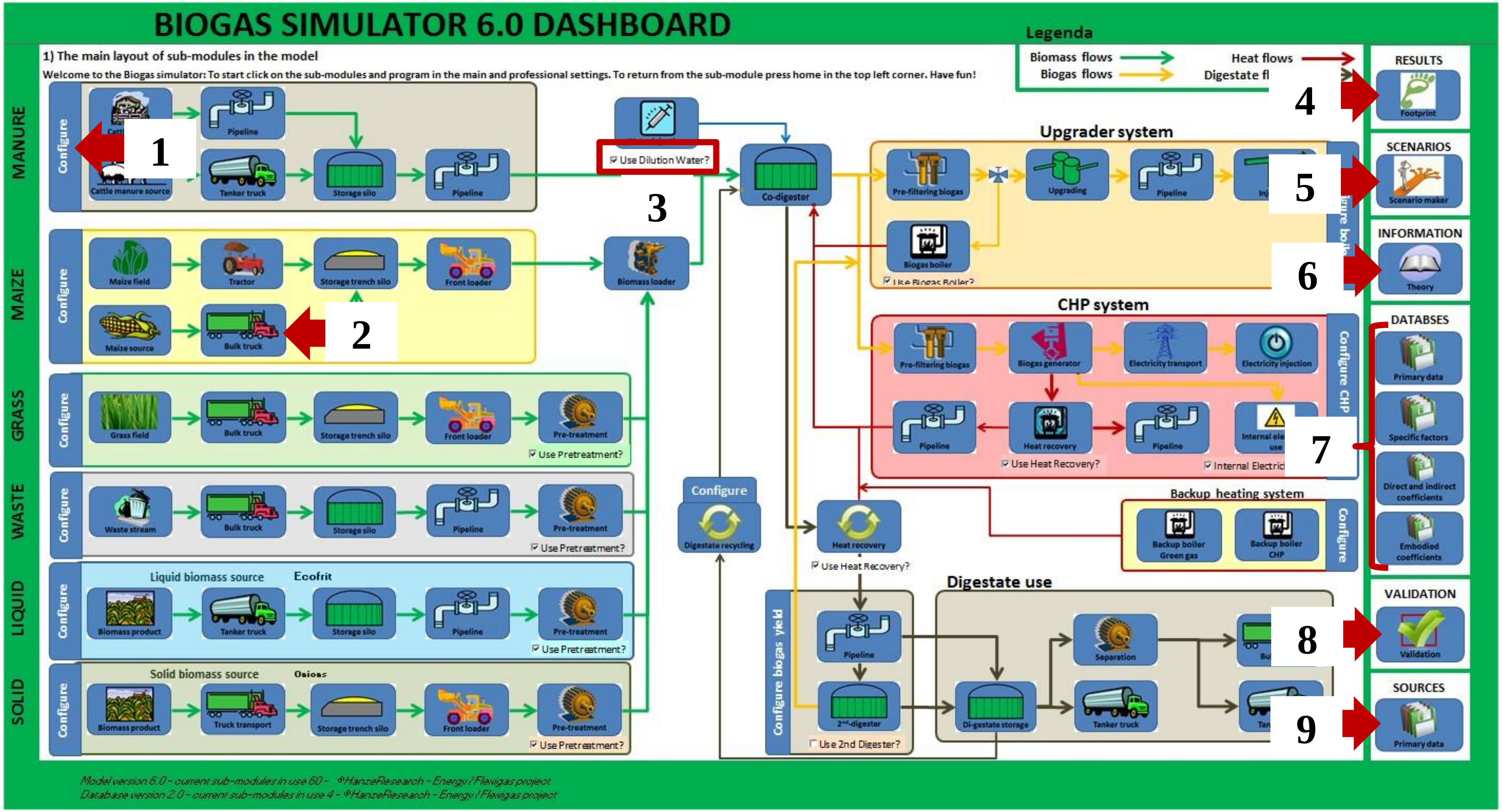
11.5 Biogas Production Model User’s Guide

Fast guide Biogas Simulator

Within the Biogas Simulator fast guide the basic requirements for operating the model are explained. If more information is needed please contact:
Frank Pierie | Hanze University of applied science |T: +31 (0)50 595 4640 | F: +31 (0)50 595 4999 | M: +31 (0)6 508 76 004 | E: f.pierie@pl.hanze.nl |

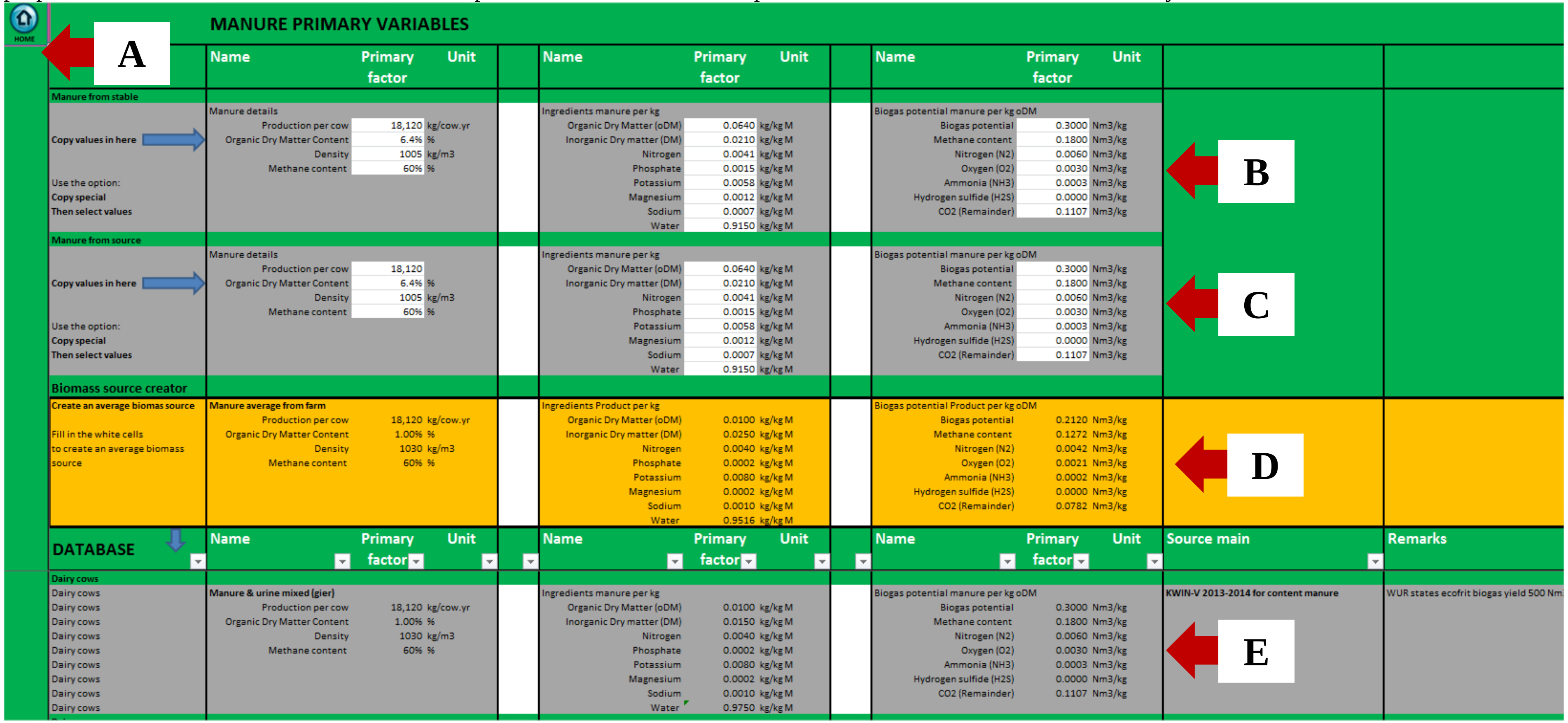
Opening the model

The starting point of the model is the Dashboard. From here you can access every sheet of the model to change values or view the results. From every other module you can always return here by clicking on the home button in the top left corner of your screen. The various sections of the dashboard will be explained in the following chapters of the fast guide.


BIOGAS SIMULATOR 6.0 DASHBOARD
1) The main layout of sub-modules in the model
Welcome to the Biogas simulator: To start click on the sub-modules and program in the main and professional settings. To return from the sub-module press home in the top left corner. Have fun!
Legenda
Biomass flows
Biogas flows
Heat flows
MANURE
MAIZE
GRASS
WASTE
LIQUID
SOLID
Configure
Cattle manure source
Pipeline
Tanker truck
Storage silo
Maize field
Tractor
Storage trench silo
Front loader
Maize source
Bulk truck
Grass field
Pre-treatment
Use Pretreatment?
Waste stream
Liquid biomass source
Ecofrit
Biomass product
Solid biomass source
Truck transport
Use Dilution Water?
Biomass loader
Co-digester
Upgrader system
Pre-filtering biogas
Upgrading
Biogas boiler
CHP system
Biogas generator
Electricity transport
Electricity injection
Heat recovery
Use Heat Recovery?
Backup heating system
Backup boiler Green gas
Backup boiler CHP
Digestate recycling
Digestate use
Configure biogas yield
2nd digester
Use 2nd Digester?
Di-gestate storage
Separation
RESULTS
Footprint
SCENARIOS
Scenario maker
INFORMATION
Theory
DATBASES
Primary data
Specific factors
Direct and indirect coefficients
Embodied coefficients
VALIDATION
Validation
SOURCES
1
2
3
4
5
6
7
8
9
Model version 6.0 - current sub-modules in use 60 - ©HanzeResearch - Energy i Flexigas project
Database version 2.0 - current sub-modules in use 4 - ©HanzeResearch - Energy i Flexigas project

1. Configuration of sections of sub-modules

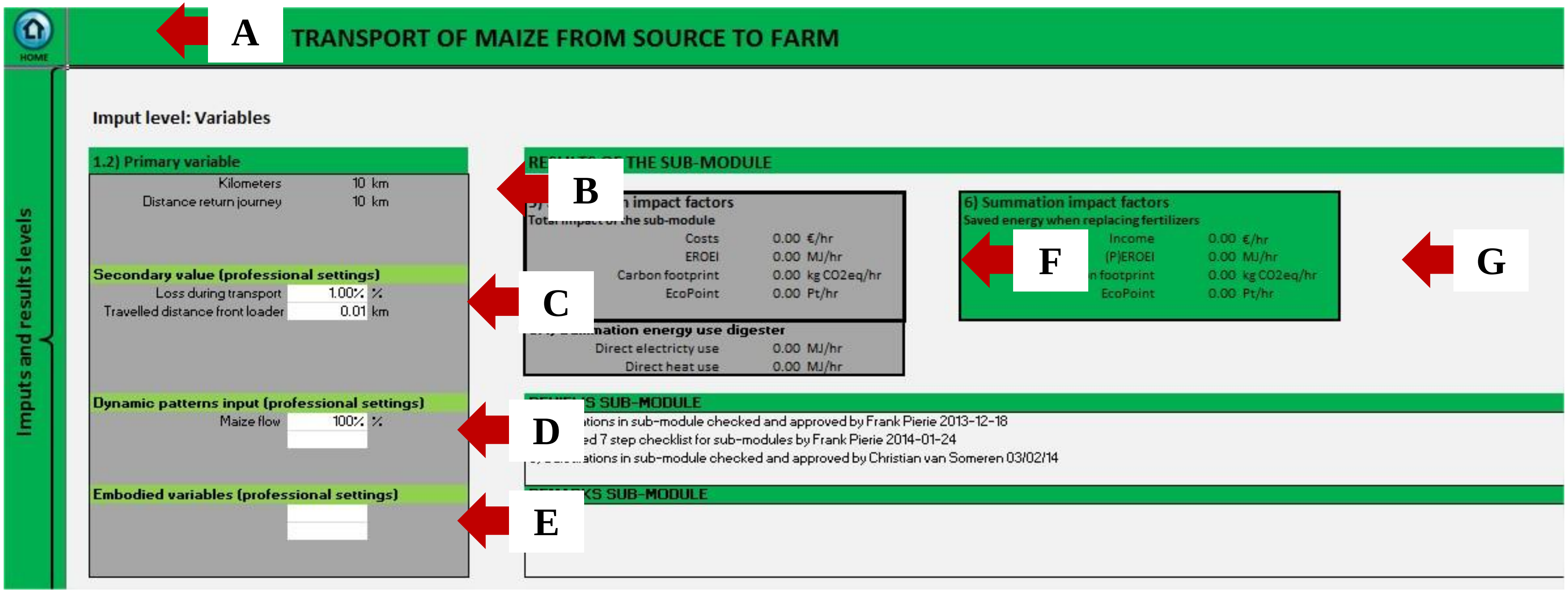
In the configuration sub-modules, the flows of biomass, digestate, exhaust gasses, etc. can be configured. In this particular case we are looking at the properties of manure from a stable and from a separate source. The main components of this sub-module are indicated by letters.



A) The home button. By clicking on the button you will return to the dashboard.
B) In this field the properties of manure from an on-site stable can be changed. For instance, the production of manure per cow per year, the nutrients in this manure or the biogas potential of this particular manure source.
C) In this field the properties of the manure from an off-site source can be changed (e.g. pig manure or cow manure). For instance, the nutrients in this manure or the biogas potential of this manure source can be altered.
D) It is also possible to configure your own specific manure source by changing the organic dry matter content. This can be done in field C. To use this data just copy the values over to Field B or C.
E) In the database, field E contains data for several types of manure. To use this data, just copy the values over to Field B or C.

2. Configuration of sub-modules

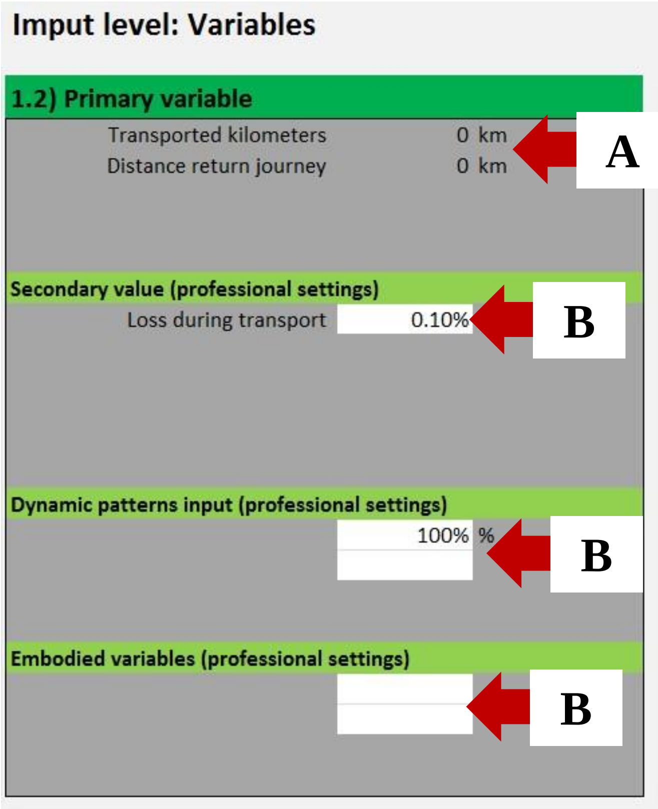
Within each sub-module there are primary and secondary variables that can be altered by the user. The main parts of this sub-module are indicated below.



A) The home button. By clicking on the button you will return to the dashboard.
B) The primary variables (e.g. amount of cows in stable, transported distance, etc.) can be filled in the white squares of the primary variable section. Primary variables indicated in yellow can be changed in the Scenarios sub-module (explained in section 5).
C) The expert variables (e.g. loss of material during transport, etc.) can be filled in the white squares of the secondary values section.
D) Dynamic variables are not used in excel version of Biogas Simulator because excel is not readily dynamic. There are exceptions in the manure stable and storage where, respectively, the time spent by cows on the field is indicated and losses of organic material during storage are indicated.
E) In the embodied variable section, the main variables of any equipment (e.g. technical lifespan, size or power of the unit) can be altered in the white squares.
F) The main Results of the sub-module: the money expended; the energy expended; the GWP100 emissions; and the environmental impact in EcoPoints.
G) The main Results of the sub-module: the money earned; the energy gained; the GWP100 emissions avoided; and the environmental impact avoided in EcoPoints.

2.1 Changeable and unchangeable variables and formulas

Additionally in the model there are inputs and calculations throughout the model, to separate the inputs from the calculation. Thus, separating the values that can be changed or not. <u>The variables that can be changed are indicated in white, whereas the variables and calculations that cannot be directly changed are indicated in grey.</u>



A) The variables indicated by A cannot be changed directly in this section, to indicate this they are colored grey.

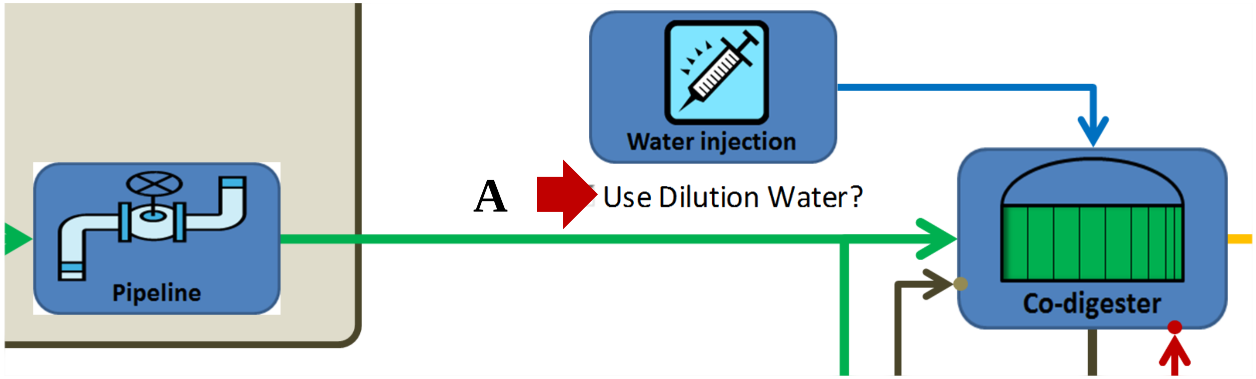
B) The variables indicated by B can be changed in this section, to indicate this they are colored white.

3. Switching specific sub-modules on or off

On the main dashboard there is the option to switch on or off certain sub-modules, which may be an unnecessary addition to the biogas production chain. The user of the model can decide to include these sub-modules or not. The sub-modules with this function are:

I) Water injection (ensures a minimum water content within the digester)
II) Biogas boiler for heating digester (if turned off, a natural gas powered boiler is turned on)
III) Heat recovery from the CHP (if turned off, additional heat requirements are provided by a biogas or natural gas boiler)
IV) Heat recovery from the digestate (if turned off, additional heat requirements are provided by a biogas or natural gas boiler)
V) Using a second digester storage system (allows for additional biogas collection)

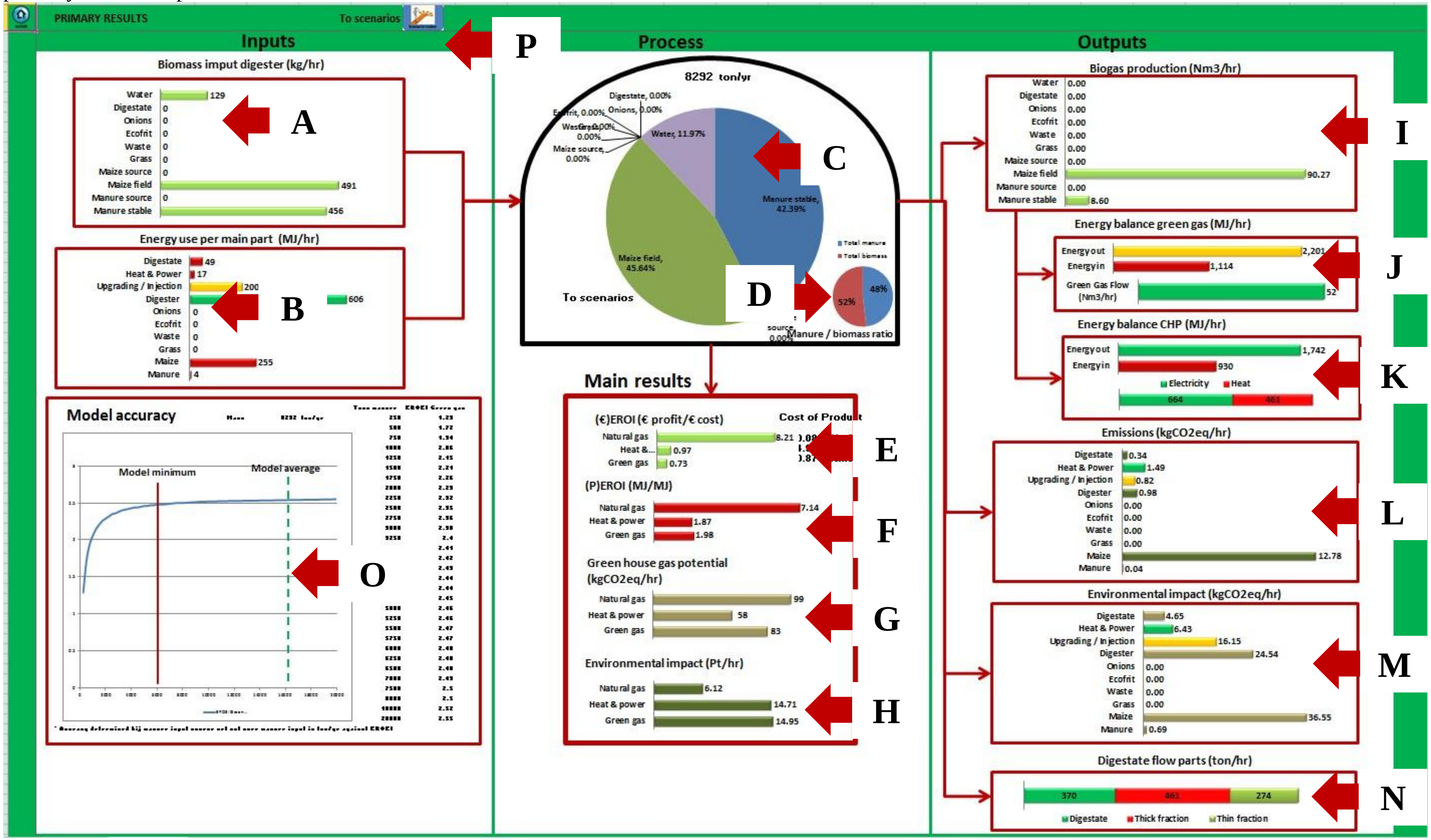
The main parts of this function are indicated with the following letters.



A) By clicking on the small box or the text indicated by the letter A, the sub-module water injection can be switched on or off, depending on the user's preference.

4. The primary results

Within the primary result sheet the main results of the scenario are depicted. The main results sheet is divided into three main parts: the primary inputs into the biogas production pathway; the process taking place in the biogas production pathway and the primary results; the outputs out of the biogas production pathway. The main parts of this sheet are indicated below.



Inputs

A) The biomass input graph indicates the biomass input into the digester in kilograms per hour
B) The energy use per main section indicates the energy used in specific sub-modules in Mega joules per hour

Process

C) Within the digester, the percentage of biomass from different sources is indicated in percentage of total input.
D) The small graph indicates the manure to biomass ratio in the biogas production pathway. In the Netherlands there are strict regulations setting this ratio to 50% manures and 50% other biomass.

Primary outputs (The primary outputs of biogas are compared to natural gas in this part)

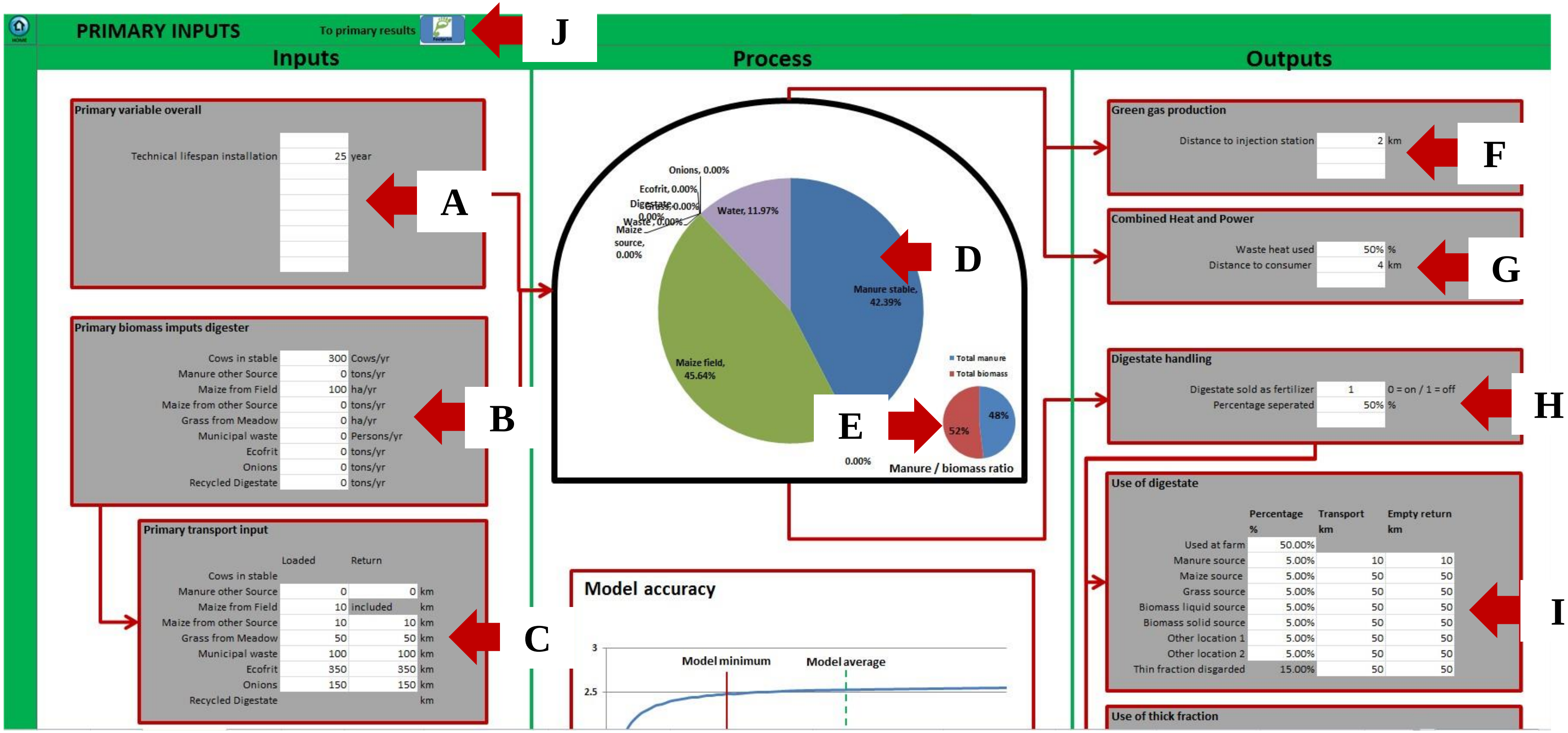
E) The first primary output indicates the money invested in physical materials (e.g. diesel, electricity, biomass, equipment etc.) to money returned through selling the main products (e.g. biogas, electricity, heat, digestate). If the ratio is lower than one there is no profit being made per hour, but if the ratio is higher than one then profit is being made. However, the ratio does not include labor of employees, interest returns on loans, etc. This indicator only focusses on the costs and returns of physical flows and is only meant as a rough guideline.
F) The efficiency of the biogas production pathway is indicated in (Process) Energy Return on Invested. For energy invested, most of the energy needed to produce the final product is taken into account, including direct (e.g. electricity), indirect (e.g. making electricity in a power plant) and embodied (e.g. the digester installation). For energy return the energy in the final product (e.g. biogas, green gas, electricity, heat or digestate) is taken into account. If the ratio is lower than one, more energy is invested into the process than is returned. If the ratio is higher than one, more energy is returned than is invested.
G) The global warming impact is indicated in Global Warming Potential or GWP100. The biomass itself is considered neutral in the process, but all the added emissions through agriculture, transport, leakage of biogas etc. are accounted for in the GWP impact factor. The Global Warming Potential is given in kilograms of carbon dioxide equivalent per hour.
H) Finally, the total damage to the environment is indicated in EcoPoints. This total score works on weighting factors for most known materials, which can be summed up to a total score in EcoPoints.

Outputs digester remainder

I) In this graph, the total biogas production per source of biomass input is given per hour.
J) In this graph, the process energy return on invested of the green gas production pathway is indicated. Also, the hourly biogas production rate is noted.
K) In this graph, the process energy return on invested of the CHP production pathway is indicated. Energy return is broken down into electricity and heat fractions.
L) In this figure, the GWP100 emissions are depicted for every main part of the biogas production chain (e.g. manure, digestion, upgrading etc.)
M) In this figure, the EcoPoints are depicted for every main part of the biogas production chain (e.g. manure, digestion, upgrading etc.)
N) In this graph, the distribution of digestate into digested, thick and thin fraction is indicated. Within the model there is the option to separate a given percentage of the digestate into a thick and thin fraction for use as fertilizer, either off-site or on-site.
O) In this graph, the sensitivity of the model is indicated. The graph indicates that an annual biomass flow of less than 6,000 tons will be less accurate.
P) In this sheet, a fast link to the scenario planner is integrated to be able to easily change primary input values and see the effects directly.

5. Scenario planning in the model

In the scenarios sheet all the data coming from the sub-modules is depicted in graphs and tables. There is also the option of changing primary input variables to see the effects of modifying the biogas production chain. The graphs are similar to the results page and will therefore not to be explained. The main functions of this sheet are indicated below.



Primary inputs

A) In this table the primary variables of the biogas production chain can be filled in. Currently, only the technical lifespan of the installation is included, but during the expansion of the model more variables can follow.
B) In this table the biomass flow into the digester can be filled in the white squares. The input flows are given in amount of cows, tons per year, available hectares and number of local inhabitants. Filling the variables here and not in the sub-modules will give you fast insight in the effect of varying inputs.
C) In this table the transport distances per biomass source to the digester can be filled in the white squares. The inputs are separated in a loaded trip distance and an unloaded trip distance for the return journey. These distances should be taken as an average travel distance for a particular biomass source.

Process

D) Within the digester, the percentage of biomass in the biogas production pathway is indicated as a percentage of total input.
E) The small graph indicates the manure to biomass ratio in the biogas production pathway. In the Netherlands there are strict regulations setting this ratio to 50% manures and 50% biomass.

Output

F) In this table the main variables of green gas production can be filled in. Currently, this is only the transport distance of the green gas to the injection station.
G) In this table the main variables of a CHP can be filled in. Currently, this includes the amount of heat recovered from the CHP unit and the distance traveled of this heat to the consumer.
H) In this table the main settings for digestion handling are indicated, where the percentage of digestate separated for off-site use can be indicated.
I) The individual digestate fractions must be allocated to different locations: These locations can either be the farm itself, one of the sources of biomass or a buyer of digestate. Transport distances to these destinations can also be indicated.
J) To be able to see the results of your programming, a fast link to the results is indicated in the scenario sheet.

6. Information on the methodology used in the model

The build-up of the model is based on an article written before the construction of the model. The most important parts of this article regarding the model are included in this sheet. You can scroll up and down in this sheet to read the extended dissertation of the article.

HOME

THEORY AND METHODOLOGY

2) EXPLENATION OF INDIVIDUAL SUB-MODULE

Within each sub-module, one main physical process of the biogas production pathway is described (see Fig. 1). Every sub-module will be capable of determining three environmental impact indicators; the efficiency in (Process) Energy Return on Investment or (P)EROI; the Carbon Footprint in carbon dioxide equivalents; and the Environmental impact in EcoPoints (these impact factors will be discussed further in section 4). The summation of impact factors from the sub-modules used in the scenario will determine the total efficiency and environmental impact of the biogas production chain. To determine the aforementioned factors, each sub-module is separated into four levels; level one, the primary (mass) flow level; level two, the direct energy and material level; level three, the indirect energy and material level; and level four, the embodied energy level. Each level will be described through the use of an existing method and will perform its own calculations (see Fig. 2). Additionally, the first three levels in the sub-module will be linked together functioning as a cascade. Level one will deliver the input, through primary functional flows, for level two; and level two will provide input, through direct functional flows, for level three. This will allow dynamics in the higher level to influence the following levels, hence, transmitting the dynamic element downstream. Level four will work independently. In the following sections (2.3.1 to 2.3.4) the four levels in the sub-module will be discussed more explicitly using the structure depicted in Fig. 2.

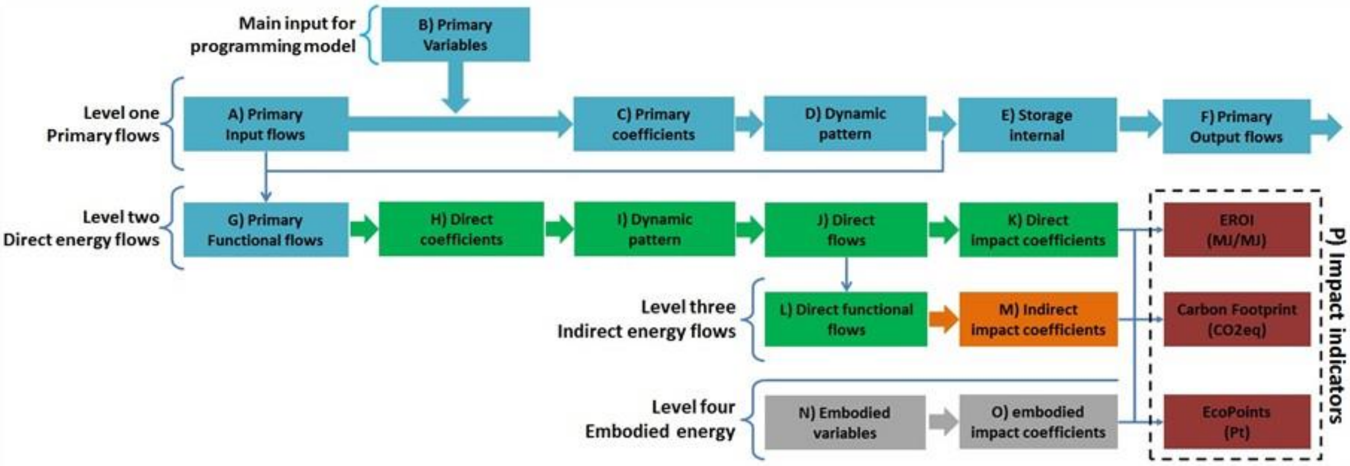


Fig. 2: Structure of a single sub-module based on dynamic MFA / MEFA / LCA

2.3.1. Level one: Primary flows

Within the metabolism concept primary mass flows are defined as raw materials, e.g., biomass, biogas, di-gestate and/or losses of the previous flows, which run through the biogas production chain. The primary mass flows which run through a single sub-module are identified and quantified through the use of the Material Flow Analysis method (MFA), which is part of the Material and Energy Flow Analysis method (MEFA).

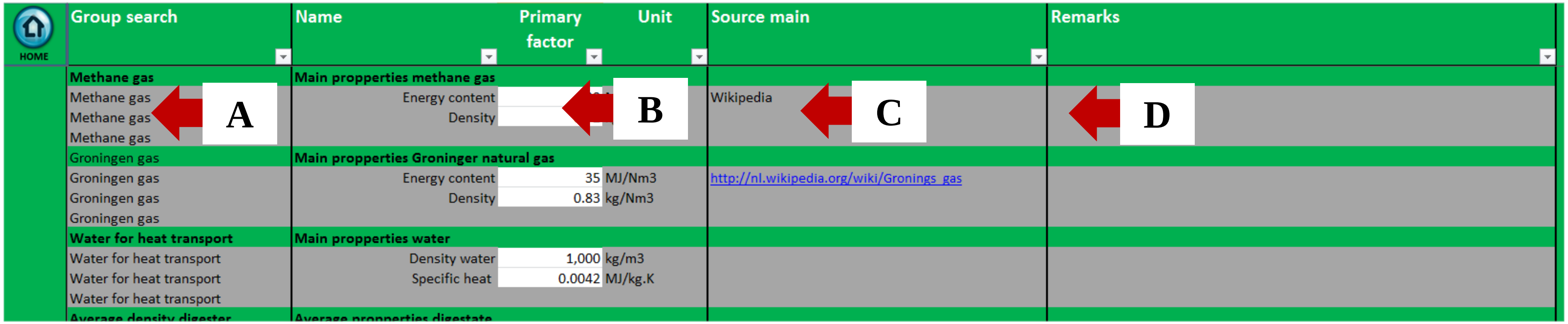
The MFA method, part of the MEFA method, as defined by Haberl and Weisz, "is a physical environmental accounting approach that tracks the use of materials, reporting the flows in physical units of mass per time index and can conceptually be linked to economic accounting frameworks. This approach is ideally suited for accounting and quantifying material requirements and waste/emissions of production systems and can be used in comparative studies, given appropriate standardization. MFA can be applied to various scales and types of systems. Overall, the MEFA framework is an integrated toolkit to account for physical flows

7. Databases

Within this model all the variables used from either literature or practice are stored in the four main databases. The values used in the sub-modules are linked to the values used in the database, meaning that if values in the database are changed, the values in the sub-modules will automatically change as well. The database itself is separated into four separate databases, namely: the primary database, mostly for physical properties of materials used in the model; the specific database, for determining the direct flows; the coefficients database, for determining the impact factors of the flows; and the embodied database, for determining the impact factors of equipment. The databases will be explained separately in this section.

7.1. The primary database

The Primary database mostly holds physical properties of energy and material flows used in the model. For instance, the density and energy content of Groninger natural gas, methane or diesel. This primary data is mostly used in the primary flow section of the sub-modules. The main parts of this sheet are indicated with the letters.

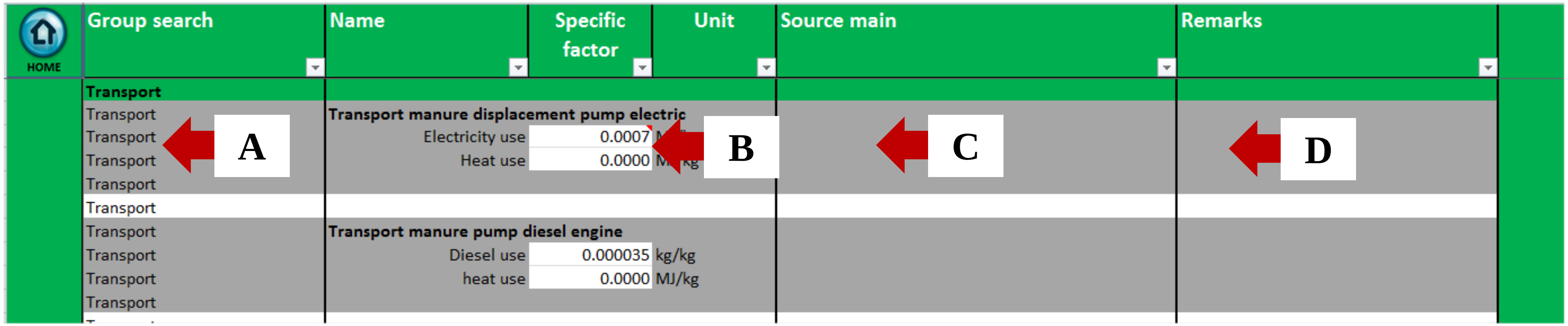


Group search	Name	Primary factor	Unit	Source main	Remarks
Methane gas	**Main propperties methane gas**				
Methane gas	Energy content			Wikipedia	
Methane gas	Density				
Methane gas					
Groningen gas	**Main propperties Groninger natural gas**				
Groningen gas	Energy content	35	MJ/Nm3	http://nl.wikipedia.org/wiki/Gronings_gas	
Groningen gas	Density	0.83	kg/Nm3		
Groningen gas					
Water for heat transport	**Main propperties water**				
Water for heat transport	Density water	1,000	kg/m3		
Water for heat transport	Specific heat	0.0042	MJ/kg.K		
Water for heat transport					
Average density digester	**Average propperties digestate**				

A) In this section the group name is filled in of the primary value.
B) In this table primary values can be filled in the white squares.
C) In this section the main source of the value can be filled in.
D) Any remarks on the primary value or source etc. can be filled in this section directly behind the primary value.

7.2. The specific database

The Specific database mostly holds coefficients to calculate direct flows, for instance the energy needed in the shape of electricity or diesel for pumping manure. This specific data is mostly used in the direct flow section of the sub-modules. The main parts of this sheet are indicated with the letters.

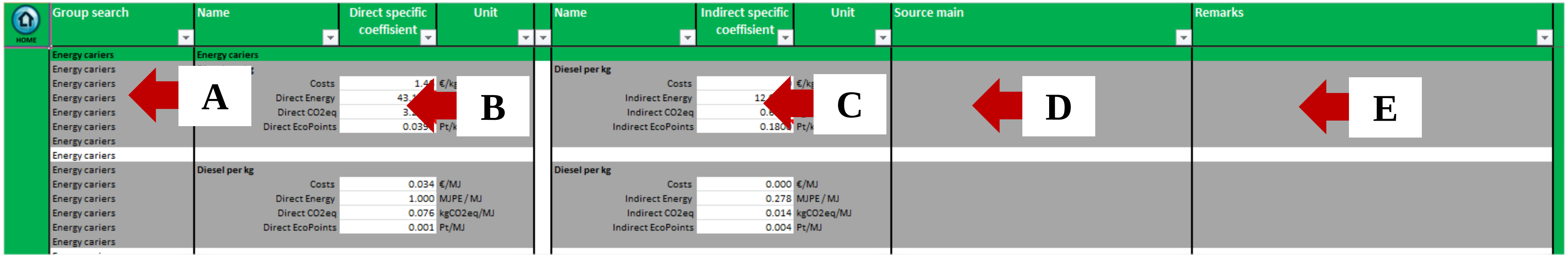


A) In this section the group name is filled in of the specific value.
B) In this table specific values can be filled in the white squares.
C) In this section the main source of the value can be filled in.
D) Any remarks on the specific value or source etc. can be filled in this section directly behind the primary value.

7.3. The direct and indirect database

The Direct and Indirect database mostly holds coefficients to calculate the impact factors of energy and material flows, for instance the impact of electricity or diesel used for pumping manure. This Direct and Indirect data is mostly used in the direct and indirect flow sections of the sub-modules. The main parts of this sheet are indicated with the letters.

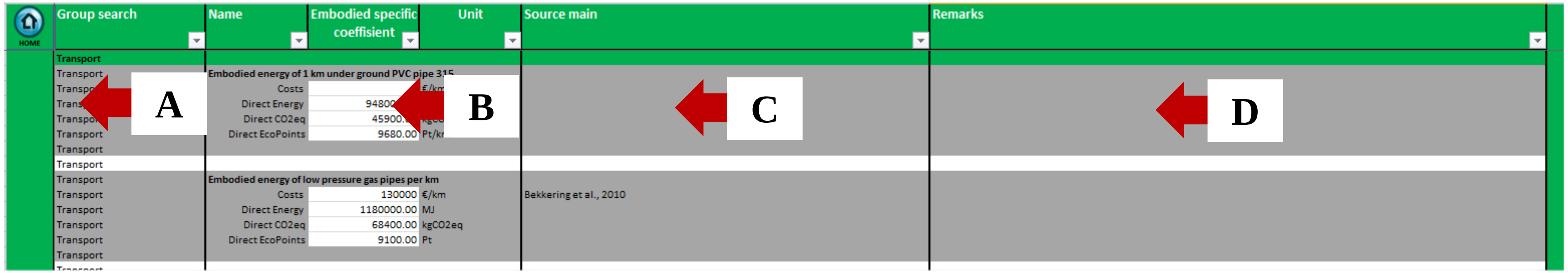
A) In this section the group name is filled in.
B) In this table direct values can be filled in the white squares.
C) In this table indirect values can be filled in the white squares.
D) In this section the main source of the value can be filled in.
E) Any remarks on the value or source etc. can be filled in this section directly behind the primary value.



7.4. The specific database

The Embodied database mostly holds coefficients to calculate the impact factors of installations present in the sub-module, for instance the impact of the digester installation. This Embodied data is mostly used in the embodied flow section of the sub-modules. The main parts of this sheet are indicated with the letters.

A) In this section the group name is filled in of value.
B) In this table embodied values can be filled in the white squares.
C) In this section the main source of the value can be filled in.
D) Any remarks on the value or source etc. can be filled in this section directly behind the primary value.



8. Validation sheet

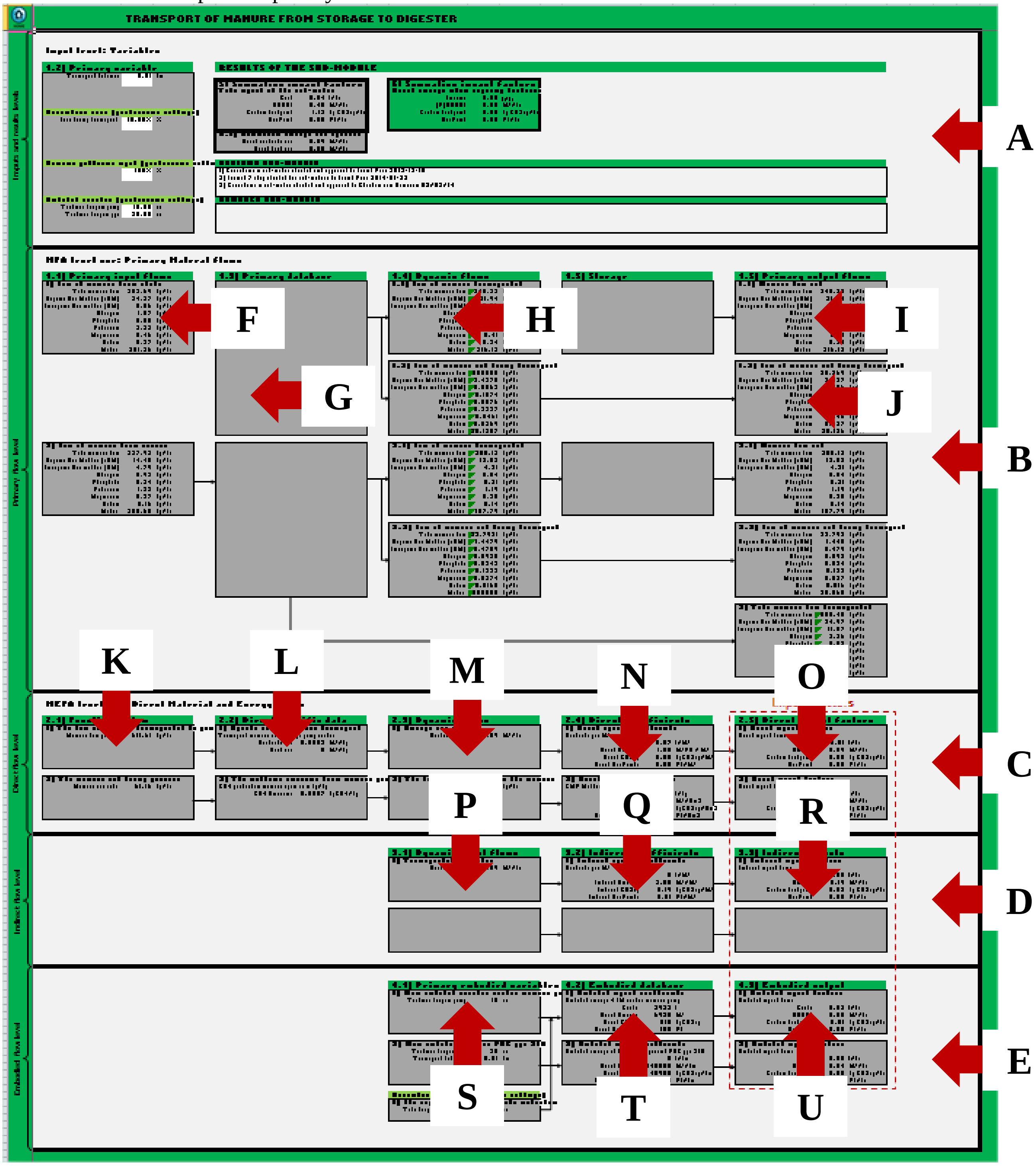
In the validation sheet data and calculations are stored that helped validate the model. Currently the data from the Dairy Campus Leeuwarden is in the validation sheet. The information of the real life digester was used to validate the biogas production calculations of the model.

9. Sources sheet

In the sources sheet all the references used to acquire the date used in the model are stated. The list of references is produced with Reworks.

10. Additional explanation of sub-modules

The sub-module is built up out of five main layers and within these layers there are input, database, calculation, and output blocks. Every sub-module has the same layout with only slight exceptions. The levels will be explained per layer.



The levels in a sub-module

A) The input and result layer houses the primary input variables and the main results, as already explained in section 3.
B) The primary flow level contains all the primary flows, which can, for example, include the flow of manure through a pipe transported from storage to the digester. The outcome of this level will become an input for a following sub-module. For instance, the output of the manure storage tank will become the input for the manure transport sub-module.
C) The direct energy and material level contain all the direct flows needed for the processing of the primary flow. For instance the use of electricity needed for pumping manure. The outcomes of the direct level will be the three main impact factors.
D) The indirect energy and material level contain all the indirect flows needed for the production of the direct energy and material flows. For instance the production of electricity needed for pumping manure. The outcomes of the indirect level will be the three main impact factors.
E) The embodied level contains all the flows needed for the production of equipment and installations present in a sub-module. For instance the impact of the digester construction. The outcomes of the embodied level will be the three main impact factors.

The primary flow level

F) The primary input from the previous sub-module is displayed in this box.
G) The primary database box contains data from the primary database to calculate the primary output.
H) Flows that act dynamically can be calculated in this box (this function is mostly unused in the excel model).
I) The primary outputs are indicated in this box, which will become an input for a following sub-module.
J) In every sub-module losses can occur, for instance losses of biomass during transport or losses through leakage of biogas out of the digester. These losses are indicated in this box and will not continue to the next sub-module. Instead they will be accounted for by impact factors in the direct and indirect level.

The direct flow level

K) The primary flows needed for the calculation of the direct energy and material flows are indicated in this box. For instance, to calculate the needed electricity of the manure pump the flow of manure must be known.
L) In this box is the specific data used for the calculation of the direct flows.
M) The resulting direct flows are displayed in this box.
N) In this box the direct impact coefficients are placed for calculating the direct impacts.
O) Finally, the direct impact factors are displayed in this box.

The indirect flow level

P) The direct flows used for calculating the indirect flows are displayed in this box.
Q) In this box the indirect impact coefficients are placed for calculating the indirect impacts.
R) Finally, the indirect impact factors are displayed in this box.

The embodied flow level

A) The variables used for calculating the embodied flows are displayed in this box.
B) In this box the embodied impact coefficients are placed for calculating the embodied impacts.
C) Finally, the embodied impact factors are displayed in this box.